AD ______________________

GRANT NUMBER: DAMD17-95-1-5019

TITLE: Development of a Telepresence Surgery System

PRINCIPAL INVESTIGATOR: Joel F. Jensen

CONTRACTING ORGANIZATION: SRI International
Menlo Park, California 94015-3493

REPORT DATE: July 1999

TYPE OF REPORT: Final

PREPARED FOR: U.S. Army Medical Research and Materiel Command
Fort Detrick, Frederick, Maryland 21702-5012

DISTRIBUTION STATEMENT: Distribution authorized to U.S. Government agencies only (proprietary information, Jul 99). Other requests for this document shall be referred to U.S. Army Medical Research and Materiel Command, 504 Scott Street, Fort Detrick, Maryland 21702-5012.

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY (Leave Blank)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	July 1999	Final (25 Oct 94 - 30 Jun 99)

4. TITLE AND SUBTITLE

Development of a Telepresence Surgery System

5. FUNDING NUMBERS

DAMD17-95-1-5019

6. AUTHORS

Joel F. Jensen

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

SRI International

Menlo Park, CA 94015-3493

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES

U.S. Army Medical Research and Materiel Command
Fort Detrick, Maryland 21702-5012

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

12a. Distribution authorized to U.S. Government agencies only (proprietary information, Jul 99). Other requests for this document shall be referred to U.S. Army Medical Research and Materiel Command, 504 Scott Street, Fort Detrick, Maryland 21702-5012.

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

Ninety percent of all deaths in wartime occur on the battlefield, before a surgeon can treat the casualty. Rapid evacuation has decreased the number of casualties dying of wounds after reaching a field hospital, but has not significantly reduced the overall death rate. The most likely reason that battlefield mortality remains high is that definitive surgical care is not available during the critical first hour after wounding. The effectiveness of trauma care is also limited by the relatively small number of surgeons with adequate experience to treat traumatic injuries. Because of prevailing peacetime conditions, fewer and fewer military medical corpsmen and surgeons have adequate experience with the types of battlefield wounds they will encounter in the line of duty. SRI has developed a revolutionary new technology—telepresence surgery—that can address both of these problems. To address the need for more rapid intervention, telepresence can enable surgeons located at field hospitals to directly and immediately treat wounded combatants at the most forward echelons of care. To improve surgeon training, SRI's telepresence technology can also be used as an advanced surgical simulation and training tool that provides a realistic training medium for practicing combat surgery in peacetime conditions.

14. SUBJECT TERMS

telepresence, telemanipulation, force feedback, remote surgery, trauma surgery, surgical simulation, surgical training, servo modeling, human factors

15. NUMBER OF PAGES

98

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	Limited

NOTICE

USING GOVERNMENT DRAWINGS, SPECIFICATIONS, OR OTHER DATA INCLUDED IN THIS DOCUMENT FOR ANY PURPOSE OTHER THAN GOVERNMENT PROCUREMENT DOES NOT IN ANY WAY OBLIGATE THE U.S. GOVERNMENT. THE FACT THAT THE GOVERNMENT FORMULATED OR SUPPLIED THE DRAWINGS, SPECIFICATIONS, OR OTHER DATA DOES NOT LICENSE THE HOLDER OR ANY OTHER PERSON OR CORPORATION; OR CONVEY ANY RIGHTS OR PERMISSION TO MANUFACTURE, USE, OR SELL ANY PATENTED INVENTION THAT MAY RELATE TO THEM.

LIMITED RIGHTS LEGEND

Award Number: DAMD17-95-1-5019
Organization: SRI International

Those portions of the technical data contained in this report marked as limited rights data shall not, without the written permission of the above contractor, be (a) released or disclosed outside the government, (b) used by the Government for manufacture or, in the case of computer software documentation, for preparing the same or similar computer software, or (c) used by a party other than the Government, except that the Government may release or disclose technical data to persons outside the Government, or permit the use of technical data by such persons, if (i) such release, disclosure, or use is necessary for emergency repair or overhaul or (ii) is a release or disclosure of technical data (other than detailed manufacturing or process data) to, or use of such data by, a foreign government that is in the interest of the Government and is required for evaluational or informational purposes, provided in either case that such release, disclosure or use is made subject to a prohibition that the person to whom the data is released or disclosed may not further use, release or disclose such data, and the contractor or subcontractor or subcontractor asserting the restriction is notified of such release, disclosure or use. This legend, together with the indications of the portions of this data which are subject to such limitations, shall be included on any reproduction hereof which includes any part of the portions subject to such limitations.

THIS TECHNICAL REPORT HAS BEEN REVIEWED AND IS APPROVED FOR PUBLICATION.

Approved 26 Oct 99

FOREWORD

Opinions, interpretations, conclusions and recommendations are those of the author and are not necessarily endorsed by the US Army.

N/A Where copyrighted material is quoted, permission has been obtained to use such material.

N/A Where material from documents designated for limited distribution is quoted, permission has been obtained to use the material.

✔ Citations of commercial organizations and trade names in this report do not constitute an official Department of Army endorsement or approval of the products or services of these organizations.

N/A In conducting research using animals, the investigator(s) adhered to the "Guide for the Care and Use of Laboratory Animals," prepared by the Committee on Care and Use of Laboratory Animals of the Institute of Laboratory Resources, National Research Council (NIH Publication No. 86-23, Revised 1985).

N/A For the protection of human subjects, the investigator(s) adhered to policies of applicable Federal Law 45 CFR 46.

N/A In conducting research utilizing recombinant DNA technology, the investigator(s) adhered to current guidelines promulgated by the National Institutes of Health.

N/A In the conduct of research utilizing recombinant DNA, the investigator(s) adhered to the NIH Guidelines for Research Involving Recombinant DNA Molecules.

N/A In the conduct of research involving hazardous organisms, the investigator(s) adhered to the CDC-NIH Guide for Biosafety in Microbiological and Biomedical Laboratories.

Joel 7 Jen 8/12/99

PI - Signature Date

CONTENTS

ILLUSTRATIONS

1. INTRODUCTION

1.1 STATEMENT OF THE PROBLEM

Ninety percent of all deaths in wartime occur on the battlefield, before a casualty has reached a surgeon (killed in action, or KIA). Rapid evacuation has been beneficial in decreasing the number of casualties dying of wounds (DOW) after reaching a field hospital, but has not significantly reduced the KIA rate. The most likely reason that battlefield mortality remains high is that definitive surgical care is not available during the critical first hour after wounding.

The effectiveness of trauma care for wounded combatants is also limited by the relatively small number of surgeons with adequate experience to treat their traumatic injuries. Training for military combat surgeons is currently based primarily on civilian trauma surgery experience, supplemented by special post-resident military training [Bowen and Bellamy, 1988]. Because of prevailing peacetime conditions, fewer and fewer military medical corpsmen and surgeons have adequate experience with the types of battlefield wounds they will encounter in the line of duty.

SRI has developed a revolutionary new technology—telepresence surgery —that can address both of these problems. To address the need for more rapid intervention, telepresence can enable surgeons located at field hospitals to directly and immediately treat wounded combatants at the most forward echelons of care, thus gaining precious minutes otherwise lost during evacuation. To improve surgeon training, SRI's telepresence technology can also be used as an advanced surgical simulation and training tool that provides a realistic haptic and visual training medium for practicing combat surgery in peacetime conditions. Through these two avenues, telepresence has the potential to significantly reduce the number of U.S. service members that are KIA.

The strength of SRI's telepresence technology derives from its unique integration of high-fidelity video, audio, and haptic (tactile) sensory inputs to the surgeon located at a hospital remote from the casualty, and the real-time, high-fidelity output to the remote surgical unit at the casualty's location, enabling precise and accurate surgical procedures to be accomplished by the telepresence surgeon. The same high-fidelity sensory feedback allows a telepresence operator's console to serve as a highly effective user interface for interacting with computer-based simulation and training models.

1.2 PROJECT GOALS AND METHOD OF APPROACH

SRI has completed three closely related projects for DARPA under the referenced grant, all of which are covered by this final report. The projects are (1) Development of an Advanced Telepresence Surgery System, (2) Telepresence Surgery Simulation, and (3) Development of a

Testbed for Telepresence Surgery at the Uniformed Services University of the Health Sciences (USUHS).

The scope of the first project, Development of an Advanced Telepresence Surgery System, was to develop, fabricate, deliver, and demonstrate a prototype advanced telepresence surgery system that could allow a surgeon, located in a mobile army surgical hospital (MASH) unit or base hospital, to carry out emergency surgical procedures on soldiers in an armored mobile surgical vehicle in the combat zone. The completed system consists of three major components:

- A mobile remote surgery unit (RSU) installed in an armored vehicle. Dubbed the *Medical Emergency Forward Area Surgical Telepresence* (MEDFAST) system, it comprises a medic-positionable pod above the surgical table, on which are mounted two 6-degree-of-freedom (DOF) slave manipulators with interchangeable surgical instruments, a pair of high-resolution video cameras (to provide a stereoscopic image pair), and additional (low-bandwidth) video cameras to provide a panoramic view of the MEDFAST vehicle interior.
- A telepresence surgeon's workstation (TSW). The TSW includes a pair of 6-DOF force-feedback master manipulators, a high-resolution stereographic display for viewing the surgical field, and auxiliary monitors for viewing the assisting medic and the inside of the MEDFAST vehicle.
- A high-data-rate, low-latency, two-way, digital, microwave communication link between the MEDFAST and the TSW. The communication link operates over a distance of up to 5 km and includes subsystems for video digitization, compression, and encoding of all signals (video, servo commands, audio, patient monitoring information), as well as modulation, demodulation, and microwave transmission.

The technology and systems developed as part of this MEDFAST development effort also played key roles in the Simulation and Testbed projects: An identical TSW (with master manipulators and stereo display) is used as the surgeon's interface in the Surgical Simulation System, where it provides a highly realistic and effective haptic and visual training interface. In the Telepresence Testbed Project, the new MEDFAST technology forms the basis for the Telepresence Surgery System to be installed at USUHS.

The scope of the second project, Telepresence Surgery Simulation, was to adapt and expand the Telepresence Surgery System so that it could serve as a surgeon's interface to virtual reality (VR) based surgical simulation and training models, and to provide a software and hardware platform that would allow surgeons to test, evaluate, and guide development of simulation models. Specifically, SRI was to develop a surgical simulation and training system consisting of

- A complete TSW, including master manipulators, stereo display, and audio feedback
- Servo control electronics, adapted for simulation

- Interface software coupling master manipulators to surgical simulation software
- Simulation engine for generating stereo display and physical modeling
- Simulation and training models imported from MusculoGraphics, Inc. (a cooperating contractor under the DARPA program)

The scope of the third project, Development of a Testbed for Telepresence Surgery at USUHS, was to provide USUHS with a complete 6-DOF MEDFAST system comprising a TSW, RSU, and system control electronics. SRI was to fabricate and assemble the system, install it at USUHS, provide technical support for system operation and maintenance, and install system upgrades that were subsequently developed under the grant.

1.3 BACKGROUND

The application of robotic technologies in surgery has grown rapidly in the last few years. Several groups have developed "image-guided" surgery systems that employ highly accurate robotic arms in combination with high-resolution image data (computed tomography [CT] and magnetic resonance [MR]) to perform precise surgical positioning and cutting under computer control [Dario et al., 1996]. For example, a specialized robotic system (MINERVA) was recently developed for stereotactic brain surgery, and conventional industrial robots have been used for placement of probes in the brain, eye, and spine [Burckhardt et al., 1995]. Typically, these computer-controlled robots insert a needle or other probe along its axis deep into a tumor, guided by skeletal structures and other positioning landmarks obtained from the CT and MR images. The "Robodoc" orthopaedic surgery system [Taylor et al., 1994], developed at IBM and Integrated Surgical Systems, is an image-guided system that functions like a CNC milling machine, producing a precise cavity in the femur for hip replacement. Also in the orthopaedic area, Kienzle et al. [1995] have developed a prototype computer-controlled system for use in total knee joint replacement. Transurethral resection of the prostate (TURP) has also been performed robotically [Ng et al., 1993].

In contrast to the robotic automation employed in image guided surgery, others have envisioned the potential advantages of telemanipulation in surgery. Alexander [1978] shows a concept for a teleoperator surgery system in which the operator could see and feel what he or she is operating on. Thring [1983] describes a bilateral surgical telerobot concept in which exoskeletal masters would be used to operate a pair of xyz Cartesian manipulators.

Marsuhima and Koyanagi [1981] describe a handheld master with a tool-like portion, and Sabatini et al. [1989] describe cutting with a finger-sized manipulator (four links) proposed for corneal transplant surgery. Gayed et al. [1987] and Guerrouad and Vidal [1989] have described the use of a stereotaxic manipulator with a remote center of rotation, for placing a probe into the eye. They used a 6-axis manipulator with joystick controls that lacked force feedback. Charles et al. [1989] describe the human-interface requirements for microsurgical telerobot surgery, Schenker et al. [1994] describe a robotically assisted microsurgery system (RAMS) aimed at enhancing surgeon dexterity in microsurgical procedures, and Hill and Jensen [1998] describe

prototype telepresence systems with applications in minimally invasive surgery (MIS), microsurgery, and remote surgery.

To address the need for remote, far-forward battlefield trauma care, the MEDFAST telepresence system needs responsive telemanipulators that allow the surgeon to remotely perform the full spectrum of surgical maneuvers—for example, cutting, suturing, dissecting—with a high degree of dexterity and effectiveness comparable to hands-on skills. Similar features are required for an effective surgical simulation and training system. Systems providing the required dexterity, speed, and delicate force feedback have not been previously developed. Only SRI's telepresence technology provides the necessary manipulation, combined with integrated stereographic and audio feedback, that makes its use natural and effective.

The SRI telepresence technology is an entirely new method of remote manipulation, with important potential applications in MIS, remote surgery, and surgical training. In 1996 SRI licensed its telepresence technology to Intuitive Surgical Corporation, a venture-funded start-up company that is currently focused on applying the technology to minimally invasive cardiac surgery. Intuitive has completed over 150 cardiac surgeries in Europe, using its latest telesurgery system, and the U.S. Food and Drug Administration (FDA) recently approved Intuitive's device for sale in the United States.

2. PROJECT ACCOMPLISHMENTS

The accomplishments for each of the three projects are described below, and are discussed in reference to the corresponding approved Statement of Work.

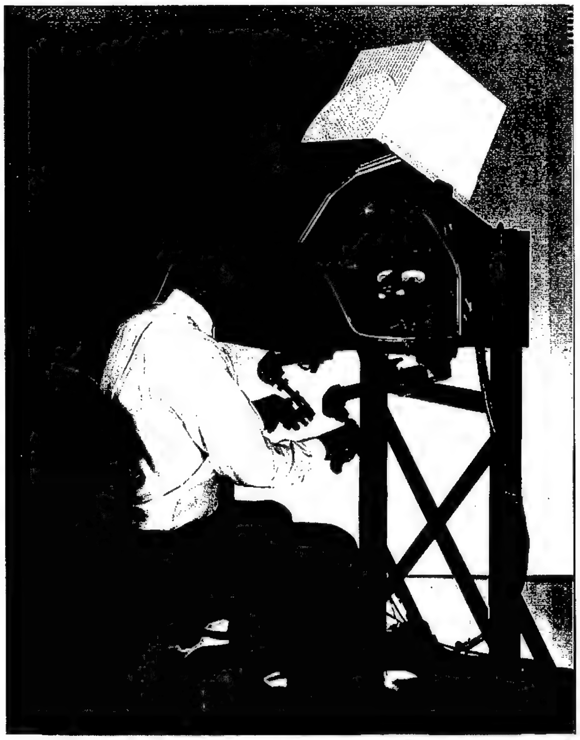
2.1 DEVELOPMENT OF AN ADVANCED TELEPRESENCE SURGERY SYSTEM

The telepresence surgery system developed under this project is shown in Figure 1, and is seen to consist of two modules: an RSU, where the remote surgery actually takes place, and a TSW with a strikingly realistic virtual workspace where the surgery *appears* to take place. This system incorporates many advanced technologies developed at SRI, including highly responsive, force-reflecting master/slave manipulators with 6 degrees-of-freedom (DOF), a 3D video display system for viewing the surgical field, and stereophonic sound. In effect, the operator grasps surgical instruments, reaches into what appears to be the actual workspace, and carries out complex tasks with quick, sure motions. Operating surgeons feel as though they are performing tasks right before their own eyes. The 3D image is created by a stereographic video system, viewed with a mirror. The surgeon looks downward, "through" the mirror, to see the surgical site below it, just where he or she is reaching with the hand controls. The left and right control handles are mounted on light, well-balanced, force-reflecting servo manipulators—the *masters*. Identical *slave* servo manipulators at the operating table support the actual surgical instrument—scalpel, forceps, and so forth—the tip of which is seen in the image, as if it were actually attached to the handle. When the tip touches the tissue, the resistance is felt through the handle. The overall effect is very compelling.

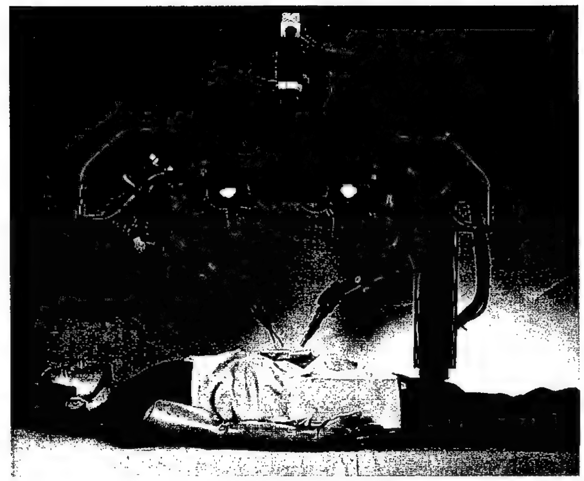
In accordance with our Statement of Work for this project, SRI organized the MEDFAST development effort into 13 major tasks. Tasks completed during Years 1 and 2 are included below for completeness. However, their status is unchanged from the most recent annual report.

2.1.1 Task 1: Mission Definition (completed in Year 1)

We consulted with combat and trauma surgeons, combat tacticians, collaborating contractors, and military telecommunications specialists to define the surgeries to be undertaken and the conditions and constraints under which the system must operate. For further information regarding the accomplishments for Task 1, refer to the project's annual report for 1996.



Telepresence Surgeon's Workstation (TSW)



Remote Surgery Unit (RSU)

Figure 1. Advanced Telepresence Surgery System

2.1.2 Task 2: System Specification (completed in Year 2)

A simplified block diagram of the overall system is shown in Figure 2. Performance, physical, and electrical specifications were established for the master and slave telemanipulators, the surgeon's video display, and the communication link between the TSW and RSU. These specifications, which formed the basis for the overall MEDFAST system design, are summarized below.

- Manipulator (left and right arms)
  - Degrees of freedom: 6 plus instrument actuation
  - Motion range: 12-in. (300-mm) cube
  - Rotational motion: 360° on tool roll and yaw axis, 150° pitch axis

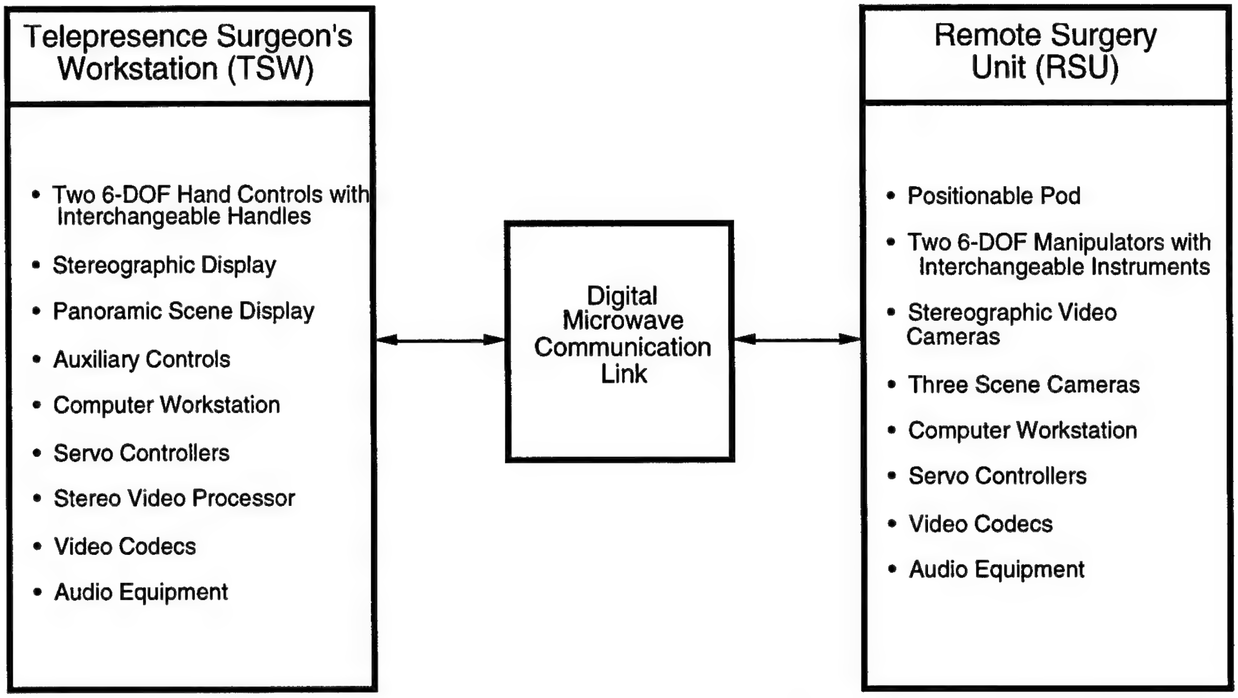


Figure 2. MEDFAST system block diagram. The complete MEDFAST system consists of the telepresence surgeon's workstation, the communication link, the remote surgery unit, and electronics modules associated with the TSW and RSU.

  - Force applied: 3 lbf (13 N)
  - Servo bandwidth: 10 Hz
  - Position resolution: 0.004 in. (0.1 mm)
  - Force resolution: 0.1 oz (0.028 N)
  - Inertia at handgrip: <100 grams

- Control handles for master manipulators, interchangeable for surgeon's use with either right or left hand
  - Hemostat handle
  - Forceps (pickup) handle
- Slave instrument interface
  - Instruments to be easily changeable automatically and by hand
  - Instruments to be sterilizable or disposable
- Jaw force and range of motion for articulated instruments
  - Hemostat: 7 lbf (opening and closing), 40°

- Needle driver: 45 lbf (closing force), 15°
- Scissors: 7 lbf (closing), 15°
- Forceps: 2 lbf (closing), 0.5 in. opening

- Stereo vision system
  - Display resolution: 640 x 480 pixels, minimum
  - Camera resolution: 700 horizontal by 494 vertical lines
  - Stereo display type: 120 Hz full-frame with active or passive glasses
- Communication link
  - Radio type: digital microwave, 2–8 GHz (line of site)
  - Signal format: standard DS3 and DS1 digital channels
  - Servo latency: 1 ms (maximum)
  - Video latency: 50 ms (maximum)
  - Range: 5 km (minimum)

2.1.3 Task 3: First Preclinical Demonstration (completed in Year 1)

Using an improved version of the SRI telepresence surgery demonstration system, we have successfully performed a series of remote surgical procedures on pigs. These first-ever remote surgeries included treatment of a variety of simulated abdominal and vascular injuries, and were performed by surgeons experienced in trauma management. The successful results of these experiments clearly demonstrate the feasibility of telepresence surgery for emergency stabilization of battlefield casualties. In addition, MEDFAST project engineers closely observed the experimental procedures and held in-depth discussions with the surgeons to gain important feedback and suggestions concerning system performance and features. The results of these experiments and discussions are serving as an important guide in the development of the advanced surgery system.

Operations were performed on 4- to 6-month-old female Hampshire farm pigs, weighing 60 to 80 pounds. The animals were housed in the AAALAC-accredited animal care facility (ACF) at UCSF, and used under an approval by the UCSF and SRI Animal Care and Use Committees. The animals were fasted, except for water, for 12 hours prior to surgery. They were premedicated in the ACF with atropine (0.05 mg/kg), ketimine (20 mg/kg), and xylazine (2 mg/kg), and then transported to the animal operating room and anesthetized with sodium pentobarbital (15–25 mg/kg with p.r.n. supplements). These were acute experiments. At the conclusion of the operations, the animals were euthanized with ketimine (20 mg/kg) and xylazine (2 mg/kg) followed by pentobarbital (150 mg/kg, IV).

All procedures attempted were completed successfully, including

- Cholecystectomy
- Nephrectomy
- Repair of gastrotomy (simulated stomach injury)
- Repair of enterotomy (simulated intestinal injury) by primary suture and by anastomosis
- Control of liver laceration
- Repair of femoral artery laceration
- Aortic interposition graft
- Repair of ureteral injury by stent placement and primary anastomosis
- Repair of bladder laceration

2.1.4 Task 4: Modeling and Mock-up (completed in Year 2)

As part of the system development process, we used computer graphics to model and evaluate designs for the TSW and RSU, and we also constructed full-scale wood and uni-strut mock-ups of the workstation, operating table, and surgical pod. These models and mock-ups have enabled surgeons and members of the design team to interact with the designs early in the development process, and feedback from these interactions has played an important role in system development. For example, before the optimized layouts for the TSW and RSU were defined, the mock-ups were used to experimentally evaluate a series of alternative mounting configurations for the master and slave manipulators. The mock-ups and models also played an important role in determining the seating geometry and location of the virtual workspace with respect to the surgeon.

2.1.5 Task 5: Communication Link Development (completed)

As shown in the block diagram of Figure 3, we developed a two-way communication link that provides a wireless connection between the TSW and the MEDFAST. All subsystems of the communication link for data compression, carrier modulation, microwave transmission, and the inverse operations were integrated, tested, and debugged, and the completed communication link was successfully used in the wireless field demonstration described Task 12. The microwave radio units were obtained on a loan basis from another DARPA-sponsored project at SRI. All other system components have been purchased specifically for the MEDFAST system.

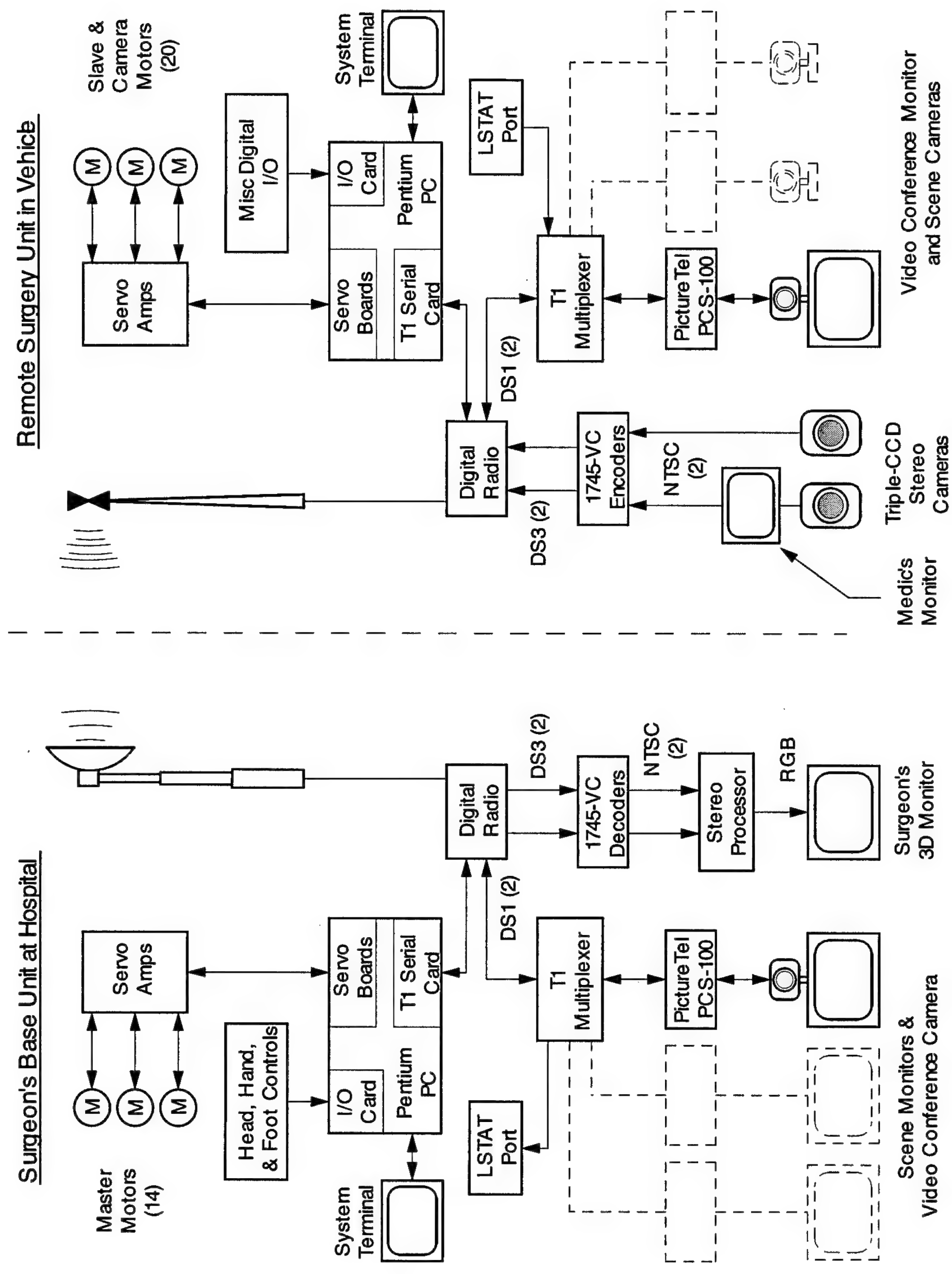


Figure 3. Communication link block diagram. Dashed lines indicate optional components.

2.1.5.1 Radio Subsystem

To implement the radio connection between the TSW and the RSU, we selected high-performance digital microwave radio units (model MDR-4208e) manufactured by Alcatel Network Systems. The MDR 4208e is a well-proven design and has a transmission capacity of two DS3 channels and two DS1 side channels. The DS3 channels (45 Mb/s) were dedicated to the stereo video for the surgeon's view, while the DS1 channels (1.54 Mb/s) carry servo data and a multiplexed data stream including auxiliary video, peripheral equipment control signals, and information on life support for trauma and transport (LSTAT).

To verify the performance of the selected radios and the overall communication link, we carried out preliminary experiments in December 1995 at SRI's radio field test site in Los Banos, California. A major goal of the field testing was to evaluate the feasibility of using a small, low-gain antenna at the MEDFAST vehicle (in combination with a relatively larger dish at the "base" site), which would have the advantages of better ruggedness and lower visible and radar cross-sections. In the tests, the mobile and base antennas were mounted on towers located 6,000 feet apart. The mobile antenna was quite small, approximately 6 inches in diameter, and was supported on a 16-foot mast. The base antenna was 6 feet in diameter and was supported on a 24-foot mast. Using this configuration, the digital communication link provided highly reliable transmission of both video and servo data in both clear and rainy weather, confirming the effectiveness of both the antenna configuration and the MDR 4208 radio units.

2.1.5.2 Video and Audio Subsystems

The RSU includes video cameras for the surgeon's stereo and scene views, and their output video streams must be digitized (via codecs) prior to radio transmission. Because the latency and resolution of the surgeon's 3D view are critical to system performance, SRI undertook a careful review of available video codecs. Our laboratory testing of the codecs included comparative and absolute resolution measurements using calibrated test charts, and latency tests using switched diode light sources and digital timing equipment. We evaluated several high-performance codec models from Northern Telecom and Alcatel Network Systems, and found that the Alcatel model 1745 VC provided the best performance in terms of our low-latency, high-resolution requirements, in part because it performs minimal signal compression. We therefore selected the 1745 VC codec for processing the 3D video. The 1745 VC also includes a pair of high-fidelity audio subchannels that will provide stereo sound feedback to the surgeon.

Latency was less of an issue for the surgeon's auxiliary scene view, and so we chose to compress the scene video (via a PictureTel PCS-100 unit) to fractional DS1 bandwidth. The PCS-100 units provide duplex transmission with good image and sound quality, and their fractional DS1 output can be multiplexed onto the radio's available DS1 bandwidth along with other data.

We originally proposed to employ a video subsystem based on SPARCstation computers using JPEG or MPEG video compression cards and ATM encoding; hence, we began Task 5 by

developing and testing a prototype system of this type in SRI's Telecommunication Technology Laboratory. However, test results with the state-of-the-art prototype system quickly revealed that the combined processes of image compression and ATM encoding resulted in video latencies of approximately 200 ms, well beyond our 30-ms requirement. We considered developing custom software and hardware to speed the compression and encoding processes, but concluded that such an effort was beyond the scope of the current project. Accordingly, we have chosen to defer the implementation of MPEG and ATM technologies until adequate systems become commercially available.

2.1.5.3 Servo Communication Subsystem

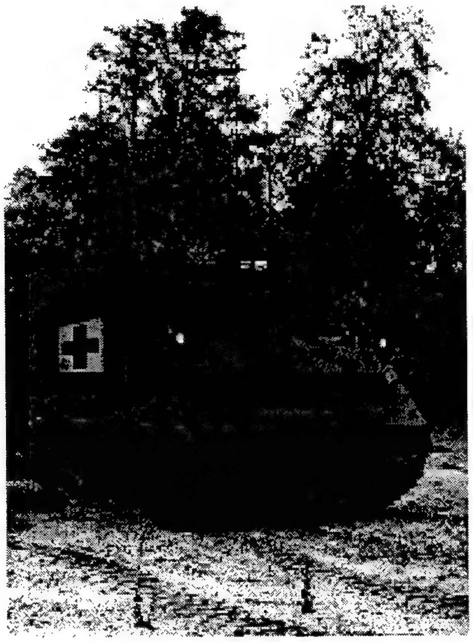
Control data were passed between the TSW and RSU servo controllers via one of the DS1 radio channels. To maximize servo performance we implemented higher-resolution (laser) position encoders on the new master and slave manipulators, resulting in a higher servo data rate compared with our original system. In the absence of compression techniques, this position data stream, in combination with force sensor data, was in excess of the 1.54 Mb/s available in the T1 channel. Therefore, in order to take full advantage of the laser encoders, we developed a lossless compression algorithm for the servo data stream based on the use of incremental position data in combination with periodic transmission of absolute information for each manipulator arm.

The servo controller cards reside in Pentium-II personal computer (PC) hosts along with T1 serial port cards. To implement the servo communication link, we developed high-speed interface software for the host PC that transfers data between the controllers and T1 ports and continuously monitors data integrity. We successfully demonstrated the servo communication subsystem as part of Task 12.

2.1.6 Task 6: Integration of Current Surgery System with MEDFAST (completed in Year 1)

The existing 5-DOF demonstration system—augmented for two-handed operation with interchangeable surgical instruments—was integrated with the MEDFAST vehicle in cooperation with Foster Miller, Inc. The integrated mobile system, shown in Figure 4, was successfully demonstrated (with a wired communication link) at the 1994 AUSA Show, the 1995 National Forum, and the Pentagon in June 1995.

In addition to integration with the MEDFAST, the telepresence surgery demonstration system underwent several major improvements: (1) Several additional types of interchangeable instruments were designed and built, including pickup-type forceps, curved dissectors, and "diamond dust" micro needle holders. (2) We have improved the responsiveness and stiffness of the manipulators, making them more sensitive to touch, through the addition of a limited integral term to the servo controller. (3) High-resolution, triple-CCD cameras with zoom lenses were added for improved stereo vision, and motorized zoom lens controls were designed and implemented. These improvements significantly increased system performance, helping to enable the successful animal surgeries that were completed as part of Task 3.



(a) Prototype MEDFAST vehicle containing remote surgery unit

(b) View inside MEDFAST vehicle showing remote surgery unit and medic assistant

Figure 4. Integrated mobile system

2.1.7 Task 7: Proof-of-Concept Demonstration (superseded)

The Task 6 configuration was originally proposed to be demonstrated with a wireless communication link as part of an Advanced Technology Demonstration (ATD) exercise. However, with the completion of Task 12, the communication link has already been successfully used for wireless operation of the new 6-DOF manipulators in the MEDFAST vehicle, making Task 7 redundant.

2.1.8 Task 8: Telepresence Surgeon's Workstation (TSW) Development (completed)

A new TSW was developed, with two 6-DOF (plus grip) hand controls, enhanced video displays, auxiliary controls, and all-new, ruggedized electronics. In designing the TSW we made extensive use of the TSW and RSU mock-ups from Task 4. Using the mock-ups, we had surgeons perform simulated surgeries, including suturing organ models, to evaluate the range of motions required for surgical procedures and guide our designs as they evolved. In completing the TSW, we evaluated its functional performance along with the rest of the MEDFAST system, using the comments of surgeons and other system users to revise and expand the TSW design. Consulting surgeons had experience in trauma, general, and vascular surgery, as well as other surgical specialties.

2.1.8.1 Subtask 8.1: Master Manipulator Design

The new manipulators were designed in accordance with the performance specification of Task 2. Major features of the manipulator design are discussed below. A more detailed description of the manipulators is in the 1996 annual report.

Manipulator Articulation: The manipulator geometry incorporates a series kinematic design with shoulder (2 DOF), elbow (1 DOF), and wrist (3 DOF) and integral handgrip actuator. All seven axes are driven by servo motors mounted at the shoulder so as to maintain a low inertia at the handgrip. The shoulder and elbow are driven through gears and push-rods while the wrist and gripper are driven through lightweight, flexible steel cables.

Wrist: The wrist incorporates bevel gears and provides roll, pitch, and yaw motions. It also incorporates a two-way drive to positively activate the tools in both opening and closing. A novel external wrist yoke provides for attachment of the slave tools and the master handgrips.

Grip Activation: Each handgrip operates a push-rod at its center that is coupled through linkages and cables to a drive motor mounted at the shoulder. The handgrips employ a special balanced mechanism that does not impart any net forces to the wrist joint during instrument actuation, and thus allows wrist-mounted force-torque sensors to be successfully employed. Such sensors would provide enhanced force feedback from the slave instruments and would also enable "power steering" of the master manipulators to minimize friction and inertial loads on the operator.

Handgrip Design: The new design allows free positioning and access throughout the workspace, and employs control handles with a pistol-grip design.

2.1.8.2 Subtask 8.2: TSW Console

Human Factors: The surgeon's console was designed to accommodate surgeons with a wide range of physical statures. The design comfortably seats men and women ranging from the 5th to the 95th percentile in height, and enables effective telepresence for all of them. Figure 5, based on data from Woodson and Conover [1964], illustrates the latitude of adjustment necessary. As shown in Figure 1, the surgeon sits on a chair that can be adjusted to the appropriate height so that his or her eyes are in the optimal location to view the display.

TSW Vision System: Both a heads-up display and a stereographic display are included in the surgeon's workstation. The heads-up display is located at the rear of the TSW console, and is positioned at approximately the same viewing distance as the stereo display to minimize the need for visual accommodation between the two views. The stereographic display is viewed through a mirror, as in our previous telepresence demonstration system, so that the surgical field appears to be located at the surgeon's fingertips. Effective visualization of the surgical field is critical to the surgeon's performance, so we carefully reviewed the state of the art in 3D vision systems to identify the best technology for the TSW vision system. After a complete evaluation of display technologies, we selected and purchased two key components for use in the TSW: (1) a five-segment liquid-crystal stereo shutter from NuVision Technologies of Beaverton, Oregon, and

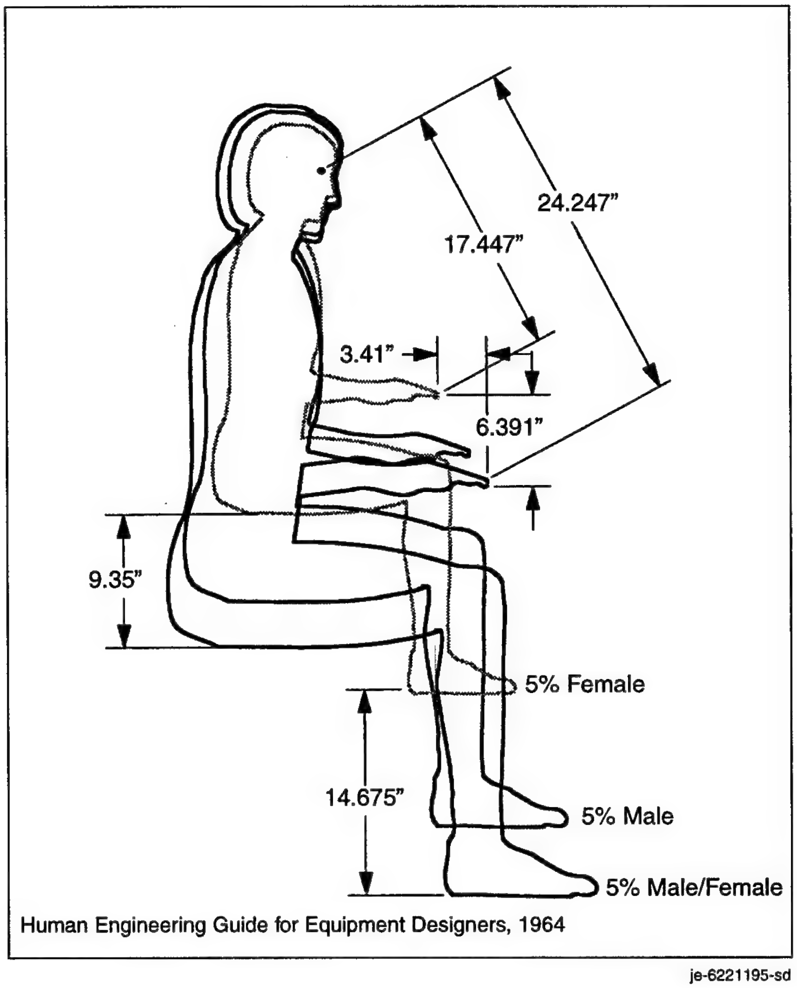


Figure 5. Variation in human dimensions

(2) a 24-bit, 40 MHz RGB stereo processor system from Imaging Technology Corporation of Bedford, Massachusetts.

In selecting the stereo shutter we evaluated a number of competing technologies, including light-valve (active) shuttered glasses, multisegment 120 Hz liquid-crystal shutters with passive glasses, and binocular head-mounted viewing systems with both liquid-crystal and cathode-ray tube displays. Objective performance was measured using precision photometry equipment and color resolution charts, and subjective data was gathered from user interviews. In terms of image resolution, brightness, and contrast, as well as crosstalk and user comfort, the recently developed 5-segment polarizing screen from NuVision (in combination with passive glasses and a high-resolution 120 Hz monitor) was found to be the most effective stereo shutter technology for use in the TSW.

To select the stereo processor for the new TSW, we evaluated the color performance, spatial resolution, and graphical-overlay capabilities of several competing systems, including units from RGB Spectrum (Alameda, California), MATROX Electronics (Dorval, Quebec), DataCube, Inc. (Danvers, Massachusetts), and Imaging Technologies. A system from Imaging

Technologies (based on its model MVC 150/40 pipeline processor) offers the best performance at a competitive price. The MVC 150/40 system provides the TSW with 24-bit "true" color and a spatial resolution of 756 x 480 pixels.

2.1.8.3 Subtask 8.3: Servo Controller

New servo electronics and system software were developed to control the 6-DOF master and slave manipulators, and we also developed servo algorithms that enable enhanced tactile feedback and dynamic response for the manipulators. To design the new algorithms we used both numerical and analytical modeling techniques, in combination with experimental testing on a single-axis servo test stand. Refer to the 1996 annual report for a complete description of the many accomplishments of Subtask 8.3.

2.1.9 Task 9: Advanced Remote Surgery Unit (RSU) Development (completed)

The new RSU is shown in Figure 1, and incorporates a medic-positionable pod with two 6-DOF (plus grip) manipulators, ruggedized electronics, and an array of interchangeable surgical instruments. The RSU of Task 9 consists of many of the same components as the TSW of Task 8, including the ruggedized electronics and the design for the manipulators, which have been previously described. Additional components for the RSU are described below.

2.1.9.1 Slave Manipulator Design

The RSU manipulators are essentially identical to the TSW master manipulators of Task 8, except that they support a range of interchangeable instruments rather than control handles. We developed a unique and effective mounting mechanism that allows these instruments to be attached to the manipulators with a simple twist-lock action, so that instrument interchange can be easily accomplished remotely (by the surgeon) or directly by hand (by the medic).

Tool Actuation: Each articulated tool is operated by a push rod at its center. Pulling the rod closes the jaws and pushing the rod opens them. Opening and closing are accomplished by a balanced spreading mechanism that does not impart any forces to the force sensor.

Tool Changer: Different tools are attached to the manipulator by using a taper (nonlocking) with antirotation pin and a spring-loaded collar to retain the tool in place. The tool mounting interface includes a unique coupling mechanism that supports differential force transmission to the tool's actuator pushrod, preventing the transmission of spurious loads to the wrist force and torque sensor. In operation, the collar can be manually slid back and the tool twisted/pulled out, or the manipulator can place the tool in a passive tool-changing rack and then twist/pull to eject it. The twist/pull operation also automatically disengages the differential-force coupling to the tool-actuation pushrod.

RSU Vision System: The RSU provides the surgeon with a "heads up" scene video in addition to a high-resolution stereo view that includes remotely controlled, motorized zoom

lenses and focus control. Because the stereo view is critical to system performance, we performed a laboratory evaluation of the leading high-performance video cameras to select the most effective model. Our test results demonstrated that the Panasonic GP-US502 provided the highest resolution (700 lines) and lowest level of fringing artifacts. Accordingly, we used a pair of these 3-CCD cameras, fitted with motorized zoom lenses, to generate the 3D view.

2.1.10 Task 10: Integration of Advanced Surgery System with MEDFAST vehicle (completed in Year 2)

In September 1996 the new RSU, including 6-DOF slave manipulators, stereo vision cameras with motorized zoom, stereo audio microphones, and medic/surgeon communication channel, was installed in an M577 Armored Ambulance for use in the Task 12 field demonstration. The M577 was outfitted (by Foster Miller, Inc.) with telesurgery support equipment, including an overhead xyz positioning gantry to support the slave manipulators and stereo cameras, lighting, storage cabinets, and a retractable surgical table for use in demonstration surgeries.

2.1.11 Task 11: Second Preclinical Demonstration (completed at USUHS)

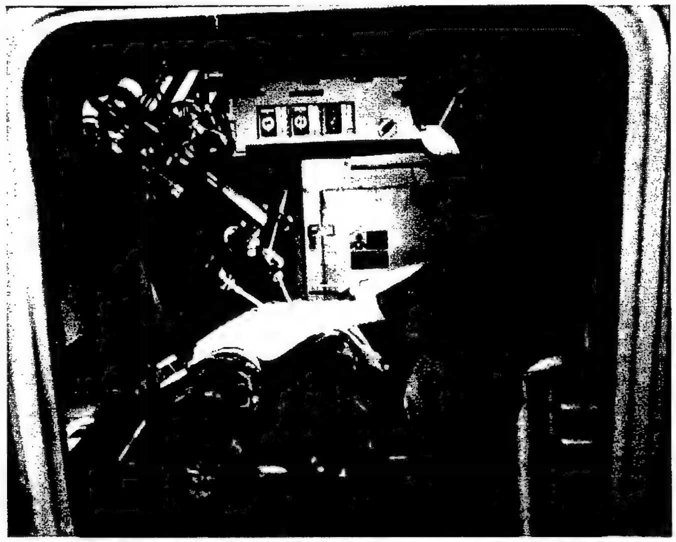
In July 1997, SRI delivered a complete advanced telepresence surgery system to USUHS as part of the third project carried out under the grant. Using this system, Dr. Christoph Kaufmann and others at USUHS have successfully carried out a set of selected surgical procedures on pigs as part of a training program for medical students at the university.

2.1.12 Task 12: Field Demonstration of Advanced MEDFAST System (completed)

On 7 and 8 October 1996, the new 6-DOF Advanced Telesurgery System was used to demonstrate wireless telesurgery on the SRI Menlo Park campus. The TSW was located in our research laboratory and was coupled via the microwave radio link to the RSU located outside in the M577 vehicle. The RSU and M577 are shown in Figures 6a and 6b. The system was evaluated by a number of visiting surgeons, including Sam Wells (President of the American College of Surgeons), all of whom commented on the effectiveness and ease of operation afforded by the new 6-DOF manipulators with their 1-ft^3 workspace and 3-pound force capacity. During the demonstration, the system was used to perform suturing and complete a dexterity test based on 3D positioning and placement tasks.

2.1.13 Task 13: Documentation (completed)

In accordance with the grant agreement for this project, SRI has submitted annual project reports and is submitting this final project report. In addition to these required reports, SRI submitted a videotape entitled "Telepresence for Far Forward Surgical Intervention on the Battlefield" on 30 November 1994, as well as a written project status report on 10 July 1995. During the system development, complete mechanical and electronic drawings and parts lists,



(a) Interior view showing the new RSU with 6-DOF slave manipulators (left side). The seated medic is shown assisting the remote surgeon.

(b) Exterior view showing the roof-mounted microwave antenna used for wireless control of the RSU mounted inside.

Figure 6. New RSU in M577 with microwave link

software, instruction manuals for purchased subsystems, and system operating instructions were prepared and compiled into manuals.

2.2 TELEPRESENCE SURGERY SIMULATION

In accordance with our Statement of Work for this project, SRI has organized the Surgical Simulation effort into three major tasks, with the goal of incorporating physically based, virtual surgical environments into the SRI Telepresence Surgery System. Our aim was to develop a platform that could be used to demonstrate and evaluate surgical simulation and training models that were being developed by other groups, including the models developed by MusculoGraphics, with support from DARPA's Biomedical Technology Program.

2.2.1 Task 1: Development of Basic Platform (completed)

We first developed a basic platform for surgical simulation incorporating simple simulation models and a single control manipulator. The platform consisted of a PC-based servo control module, a single 6-DOF control manipulator, and an (SRI-owned) SGI graphics workstation for running the surgical model. We used this platform for initial design and testing of our control algorithms and for developing the human interface. Specific accomplishments for this task include the following.

Control Interface: Because of the enormous number of calculations required to simulate deformable tissues, visual display update rates with state-of-the-art graphics workstations are typically limited to about 20 Hz. If the graphics engine were used to calculate haptic (force-feedback) signals for the simulation environment, this same low update rate would be imposed on the force-feedback and control loops—with undesirable effects on system performance. In the case of force feedback, the low update rate would cause an annoying 20 Hz buzzing vibration in the control manipulator. The effect on the servo control loop would be to limit its bandwidth, causing the surgical instruments to feel spongy or rubbery.

To avoid these pitfalls we developed a system in which the haptic calculations and graphics processing are performed on separate computers. By using this approach we are able to maintain a force and servo update rate in excess of 1 kHz, and thus avoid buzzing or spongy behavior. By separating the visual and haptic models we can reduce the complexity of the haptic model as needed to achieve adequate processing speed, while maintaining a high-quality visual rendering. Since humans are much more sensitive to visual details than haptic details, this approach yields substantial benefits.

To implement this system, SRI developed a serial interface between the Pentium II PC system and the SGI workstation and also developed software to transfer positions and forces to and from the simulation software. For positioning the simulated tools, we developed the kinematic solution for the manipulators, and for force feedback we developed their Jacobians. The kinematic solutions and Jacobians are modular so that code for different manipulators can be quickly developed as needed.

Development Hardware: To carry out our development work, we designed, purchased, and assembled a PC-based servo control module consisting of a commercially available DSP servo control board and servo amplifier boards packaged in a small electronics cabinet.

Simple Models: To test and debug our Phase I platform, we developed simple simulation models for a blunt surgical probe that moves according to input commands following the master manipulator. The manipulator kinematics software with Jacobian for force generation were implemented to make the virtual tools move according to manipulator input from the master. In addition, we generated a simple compliant model—consisting of a 3-sided "box" with compliant walls—for testing and debugging initial system operation.

System Integration and Evaluation: We integrated the SGI workstation, the servo PC computer, and the master manipulator controllers into a complete and functional Phase I simulation system, and used the system to evaluate our design approach and gather data to guide the design of the final Phase II simulation platform.

2.2.2 Task 2: Integration with SRI Telesurgery Demonstration System (superseded)

SRI originally proposed to develop an intermediate-stage platform using SRI's original 4-DOF telepresence system in combination with SRI's Reality Engine image processing computer. At the conclusion of Task 1, however, our progress in software and kinematic algorithm development was ahead of schedule and so we were able to move directly to implementing the full 6-DOF final system in Task 3.

2.2.3 Task 3: Upgrade to 6 DOF and Integration with MEDFAST (completed)

Specific accomplishments for Task 3 included the following.

Implementation with 6-DOF Manipulators of MEDFAST TSW: We expanded the Task 1 system to accommodate the 6-DOF (plus grip) master manipulators of the newly developed SRI MEDFAST system. This step included changing the Jacobians and kinematic equations to expand both position-out and force-in calculations from 3 axes to 14 axes of motion.

Implementation of Instrument Models: We expanded the simulation to include virtual surgical instruments (clamps and forceps) like those we developed for the MEDFAST system.

Incorporation of Simulation Models and Demonstration of System: We imported the intravenous (IV) needle insertion trainer and the leg trauma simulation (LTS) models produced by MusculoGraphics, and demonstrated operation of these models on the SRI platform. With the completion of this step, it became possible to use the TSW to perform actual remote surgery as well as practice surgery on virtual models. In fact, the surgeon or trainee can switch seamlessly between the two modes with a few simple keystrokes.

Installation of SRI Simulation Platform at USUHS: To provide increased access to the SRI simulation platform, we installed the platform at USUHS where it will form part of the new

Simulation and Readiness Center that is nearing completion there. While this effort was beyond the scope of the proposed work, we felt that it was important to make the system more widely available, and we were able to complete the installation within our original budget. The installation effort involved upgrading the MEDFAST system we installed there in July 1997, and included supplying and integrating a new Pentium-II host computer for the servo system, installing upgraded software and cabling, and training USUHS staff to operate and maintain the system.

2.3 TESTBED FOR TELEPRESENCE SURGERY AT USUHS

The scope of this effort was to provide USUHS with a complete 6-DOF MEDFAST system comprising a TSW, RSU, and system control electronics. SRI fabricated and assembled the complete system, installed it at USUHS, provided technical support for system operation and maintenance, and installed system upgrades that were subsequently developed under the grant. As proposed, the project was divided into four tasks.

2.3.1 Task 1: System Fabrication (completed)

SRI purchased, fabricated, and assembled all the components required for the complete, 6-DOF prototype MEDFAST system, including a TSW, RSU, and control module. The TSW included a complete 3D viewing system, telesurgical instrument control handles, ergonomic seating for the surgeon, and scene LCD monitors. The RSU included high-resolution, color CCD cameras for stereo viewing, a scene CCD camera, manipulator arms with manually interchangeable surgical instruments, and lighting. Audio linkage between the TSW and RSU was also included. The assembled system is identical to the one shown in Figure 1, and was fully tested and debugged at SRI facilities in Menlo Park before shipment to USUHS in July 1997.

2.3.2 Task 2: Preparation of Facilities, Shipment and Installation of System (completed)

In conjunction with USUHS, SRI determined the modifications required to the USUHS physical plant to accommodate the telepresence surgery system. SRI disassembled the telepresence surgery system, purchased and fabricated padded cases and transport crates, and packaged and shipped the system from SRI in Menlo Park to USUHS in Bethesda. We then unpacked and assembled the telepresence surgery system at USUHS, and tested it to confirm that all subsystems were functioning properly.

2.3.3 Task 3: System Operation and Scientific Testing (completed)

A scientific testing program for the telepresence system was designed and carried out by USUHS staff under the direction of Dr. Kaufmann. The system performed very reliably, and only minimal technical support from SRI was needed. Dr. Kaufmann continues to use the system in his teaching and research programs at USUHS.

2.3.4 Task 4: System Maintenance, Support, and Upgrades (completed)

SRI provided three major upgrades for the SRI telepresence system at USUHS. First, we designed, fabricated, and delivered additional surgical instruments for the system as requested by Dr. Kaufmann, including surgical "pick-up" forceps, curved forceps, and improved needle holders. In the next upgrade, we installed a higher-resolution (756 x 480 pixel) 24-bit RGB color stereo processor that we had under development to replace the existing NTSC stereo processor. Our final upgrade was a major effort that enabled the TSW to be used as an interface to access computer-based surgical simulation and training models. This upgrade was carried out as an extension of the Telepresence Surgery Simulation project as described in Section 2.2

2.4 KEY RESEARCH ACCOMPLISHMENTS

- In April 1995 we used an improved version of the SRI telepresence surgery demonstration system to successfully perform a series of remote surgical procedures on pigs. These first-ever remote surgeries included treatment of a variety of simulated abdominal and vascular injuries, and were performed by surgeons experienced in trauma management. The successful results of these experiments clearly demonstrated the feasibility of telepresence surgery for emergency stabilization of battlefield casualties. All procedures attempted were completed successfully.

- On 28 August 1996, we demonstrated remote telesurgery operation using the DARPA-funded National Transparent Optical Network Consortium (NTONC) fiber-optic lines as the communication link. In this demonstration the 4-DOF SRI system was operated over a 300-km multiple-wavelength all-optical network (including optical switches and amplifiers) provided by the NTONC project at Lawrence Livermore National Laboratory (Livermore, California). The TSW was located at the national laboratory in Livermore, and the RSU was located at SRI (Menlo Park, California). Consortium executives as well as DARPA program manager Bert Hui used the system during a project meeting and were impressed with the effectiveness of the telepresence technology and its ability to operate over long distances.

- On 7 and 8 October 1996, we demonstrated wireless telesurgery with the new 6-DOF Advanced Telesurgery System. The TSW was located in our research laboratory in Menlo Park and was coupled via a microwave radio link to the RSU located outside in an M577 armored ambulance. The system was evaluated by a number of visiting surgeons, including Sam Wells (President of the American College of Surgeons), all of whom commented on the effectiveness and ease of operation afforded by the new 6-DOF manipulators with their 1-ft^3 workspace and 3-pound force capacity. During the demonstration, the system was used to perform suturing and complete a dexterity test based on 3D positioning and placement tasks.

- In July 1997, SRI delivered a complete, 6-DOF prototype MEDFAST system to USUHS, including a TSW, RSU, and control module. The TSW included a complete 3D viewing

system, telesurgical instrument control handles, ergonomic seating for the surgeon, and scene LCD monitors. The RSU included high-resolution, color CCD cameras for stereo viewing, a scene CCD camera, manipulator arms with interchangeable surgical instruments, and lighting. An audio communication link between the TSW and RSU was also included.

- In June 1999, we installed, at USUHS, a Telepresence Simulation platform that enables surgeons and medical students to interact with computer-based surgical simulation and training models using the MEDFAST TSW. The TSW provides advanced haptic and visual interfaces, with force and torque feedback on all 6 DOF of the master manipulators and high-resolution stereo video. The MEDFAST and Telepresence Simulation platform are expected to play an important role in the new Simulation and Readiness Center that is nearing completion at USUHS.

2.5 REPORTABLE OUTCOMES

In addition to successfully completing the projects and tasks discussed above, the work carried out by SRI has resulted in numerous scientific publications, including the following:

Hill, John W., Joel F. Jensen, Philip S. Green, and Ajit S. Shah, "Two-Handed Telepresence Surgery Demonstration System," *Proc. ANS Sixth Annual Topical Meeting on Robotics and Remote Systems*, Monterey, Vol. 2, pp. 713–720, February 5–10, 1995.

Green, Philip S., John W. Hill, Joel F. Jensen, and Ajit S. Shah, "Recent Developments in Remote Telepresence Surgery," presented at Medicine Meets Virtual Reality III, San Diego, January 19–22, 1995.

Jensen, Joel F., John W. Hill, Philip S. Green, and Ajit S. Shah, "Remote Telepresence Surgery," presented at Emergency Medicine, the Next Hundred Years, San Francisco, March 23–24, 1995.

Green, Philip S., John W. Hill, Joel F. Jensen, and Ajit S. Shah, "Telepresence Surgery," *IEEE EMBS Magazine*, Vol. 14, No. 3, pp. 324–329, May/June 1995.

Green, Philip S., J. F. Jensen, J. W. Hill, and A. S. Shah, "Mobile Telepresence Surgery," *Proc. Second Annual Symposium on Medical Robotics and Computer Assisted Surgery,* Baltimore, pp. 97–103, November 4–7, 1995.

Bowersox, Jon C., et al., "Complex Task Performance in Cyberspace," presented at Medicine Meets Virtual Reality III, San Diego, January 17–20, 1996.

Jensen, Joel F., and John W. Hill, "Advanced Telepresence Surgery System Development," *Proc. MMVR4,* San Diego, January 17–20, 1996.

Bowersox, Jon C., Ajit S. Shah, Joel F. Jensen, John W. Hill, and Philip S. Green, "Vascular Applications of Telepresence Surgery: Initial Feasibility in Swine," *J. Vasc. Surgery*, pp. 281–287, February 1996.

Jensen, J.F., and J.W. Hill, "Remote Telepresence Surgery," presented at Medicine 2001, Montreal, June 1996.

Jensen, J.F., and R. Li, "Laparoscopic Telepresence Surgery: Performance Evaluation of a Prototype System," presented at Medicine Meets Virtual Reality 5, San Diego, January 24, 1997.

Hill, John W., and Joel F. Jensen, 1997: "Telepresence Technology in Medicine: Principles and Applications," *Proc. IEEE*, Vol. 86, No. 3, pp. 569–580, March 1998.

3. CONCLUSIONS

In successfully completing the three projects covered by this report (Advanced Telepresence Surgery System, Surgical Simulation, and Telepresence Testbed for USUHS), SRI has substantially advanced the state of the art in the fields of telepresence surgery and surgical simulation and training. By developing and demonstrating the MEDFAST telesurgery system, we have clearly proven the technical feasibility of performing remote, wireless telesurgery to provide trauma care to wounded personnel. No system like the MEDFAST existed prior to this development effort, and the Telepresence Testbed at USUHS can now serve as a technology center that will build on our work and define the next steps to be taken toward practical field implementation. In the area of Surgical Simulation, the SRI Surgical Simulation platform we installed at USUHS provides a level of realism and haptic fidelity that is unmatched by any other system. As a result, the USUHS Testbed can also serve as a basis from which to specify and design the next-generation simulation and training systems, and important user feedback can be provided by the medical students and surgical staff at that facility.

With the ever-increasing network speed and computer processing power that becomes available each year, the telepresence and simulation technologies represented by the SRI systems will rapidly become more powerful and more cost-effective to implement. In the near future, low-orbit satellites will be available to provide high-bandwidth, low-latency communication links for wireless telepresence surgery. For simulation, increased processing speed and memory capacity will enable simulation systems that provide unprecedented realism in surgical planning based on software models with patient-specific anatomy.

It is also important to note that the telepresence technology developed by SRI under this grant can potentially be of significant value to a wide range of military customers. The key areas of technology development are

- Integration of a range of advanced control, display, and robotic technologies to create a transparent, yet immersive, interface that enables a human to effectively carry out remote manipulation tasks and can also serve as a surgical simulation user interface of unparalleled fidelity and realism
- Development of advanced control algorithms to provide a natural haptic interface to the remote world
- Development of state-of-the-art 6-DOF master and slave manipulators
- A unique mapping strategy between master and slave to enable effective human-in-the-loop control

Several branches of the military as well as non-DOD customers stand to benefit from these technologies. Some of the key customers and their potential applications are

- U.S. Army: Telepresence surgery for remote combat casualty care and local treatment of individuals (in containment facilities) exposed to biological or chemical agents
- U.S. Navy: Medical care between carriers and other ships in fleet without the necessity to transport medical personnel
- Explosive Ordnance Disposal (EOD): Capability for EOD technicians to remotely investigate and disarm unexploded ordinance, terrorist devices, and mines without exposing personnel to risk of injury from accidental explosions

4. REFERENCES

Alexander, A.D., "Impacts of Telemation on Modern Society," *First IFToMM Symposium*, Vol. 2, p. 122 (1978).

Bowen, T.E., and Bellamy, R.F., *Emergency War Surgery*, United States Government Printing Office, Washington D.C., 1988

Burckhardt, C.W., P. Flury, and D. Glauser, "Stereotactic Brain Surgery," *IEEE EMBS Magazine*, Vol. 14, No. 3, pp. 314–316 (May/June 1995).

Charles, S., R.E. Williams, and B. Hamel, "Design of a Surgeon-Machine Interface for Teleoperated Microsurgery," *Proc. IEEE Engineering in Medicine and Biology*, 11th Annual Int. Conf., pp. 883–884 (1989).

Dario, P., et al., "Robotics for Medical Applications," *IEEE Robotics & Automation Magazine*, September 1996, pp. 44–56.

Gayed, M.B., et al., "An Advanced Control Manipulator for Surgical Applications," *Systems Science*, Vol. 13, pp. 123–134 (1987).

Guerrouad, A., and P. Vidal, "SMOS: Stereo-telemanipulator for Ocular Surgery," *Proc. IEEE Engineering in Medicine and Biology*, 11th Annual Int. Conf., pp. 879–880 (1989).

Hill, J.W., and Jensen, J.F., "Telepresence Technology in Medicine: Principles and Applications," *Proceedings of the IEEE*, Vol. 86, No. 3, March 1998, pp. 569-580.

Kienzle, et al., "Total Knee Replacement," *IEEE Engineering in Medicine and Biology*, Vol. 14, No. 3, May/June 1995, pp. 301–306.

Marsuhima, K., and H. Koyanagi, "Servo Micromanipulator 'Tiny-Micro Mk. I'," *Fourth CISM-IFToMM Symposium*, p. 251 (1981).

Ng, W.S., B.L. Davies, R.D. Hibberd, and A.G. Timoney, "Robotic Surgery: A First-Hand Experience in Transurethral Resection of the Prostate," *Proc. IEEE Engineering in Medicine and Biology*, pp. 120–125 (1993).

Schenker, P., et al., "Small Surgery, Big Results," *NASA Tech Briefs*, November 1994, p. 16.

Taylor, R.H., et al., "An Image-Directed Robotic System for Precise Orthopaedic Surgery," *IEEE Trans. Robotics and Automation*, 10(3), 261–265 (1994).

Sabatini, M., M. Bergamasco, and P. Dario, "Force Feedback-Based Telemicromanipulation for Robot Surgery on Soft Tissues," *Proc. IEEE Engineering in Medicine and Biology*, 11th Annual Int. Conf., pp. 890–891 (1989).

Thring, M.W., *Robots and Telechirs*, Ellis Horwood Ltd. (1983).

Woodson, W., and D. Conover, *Human Engineering Guide for Equipment Designers*, 2nd Edition, University of California Press (1964).

APPENDIX A: PERSONNEL RECEIVING PAY FROM THE RESEARCH EFFORT

The following key project staff received pay from this research effort:

Jon C. Bowersox, M.D., Ph.D.

Maxwell Crittenden, B.S.

Yonael Gorfu, Ph.D

Philip S. Green, M.S.

Gary Guthart, Ph.D.

Jon Heim, B.S.

John W. Hill, Ph.D.

Peter Holst, M.S.

Joel F. Jensen, M.S.

Thomas Low, M.S.

C. Lynn Mortensen, B.S.

Peter Schattner, Ph.D.

Ajit Shah, Ph.D.

Information regarding additional staff who received pay as part of this research effort can be obtained from SRI through standard DCAA auditing processes.

APPENDIX B: SUPPORTING PUBLICATIONS

The attached publications are related to the research conducted.

Vascular applications of telepresence surgery: Initial feasibility studies in swine

Jon C. Bowersox, MD, PhD, Ajit Shah, PhD, Joel Jensen, MS, John Hill, PhD, Paul R. Cordts, MD, and **Philip S. Green, MS,** *Bethesda, Md., Menlo Park, Calif., and Honolulu, Hawaii*

Purpose: **Telepresence surgery is a novel technology that will allow procedures to be performed on a patient at locations that are physically remote from the operating surgeon. This new method provides the sensory illusion that the surgeon's hands are in direct contact with the patient. We studied the feasibility of the use of telepresence surgery to perform basic operations in vascular surgery, including tissue dissection, vessel manipulation, and suturing.**

Methods: **A prototype telepresence surgery system with bimanual force-reflective manipulators, interchangeable surgical instruments, and stereoscopic video input was used. Arteriotomies created ex vivo in segments of bovine aortae or in vivo in femoral arteries of anesthetized swine were closed with telepresence surgery or by conventional techniques. Time required, technical quality (patency, integrity of suture line), and subjective difficulty were compared for the two methods.**

Results: **All attempted procedures were successfully completed with telepresence surgery. Arteriotomy closures were completed in 192 ± 24 sec with conventional techniques and 483 ± 118 sec with telepresence surgery, but the precision attained with telepresence surgery was equal to that of conventional techniques. Telepresence surgery was described as intuitive and natural by the surgeons who used the system.**

Conclusions: **Blood-vessel manipulation and suturing with telepresence surgery are feasible. Further instrument development (to increase degrees of freedom) is required to achieve operating times comparable to conventional open surgery, but the system has great potential to extend the expertise of vascular surgeons to locations where specialty care is currently unavailable. (J VASC SURG 1996;23:281-7.)**

Surgery has always required that the hands of a surgeon be placed directly in a wound. The rapid emergence of minimally invasive surgery, however, has conclusively proven that for many procedures indirect tissue visualization and manipulation can provide results that are at least as good as those obtained with a conventional open approach.[1,2] In vascular surgery, percutaneous endovascular techniques have been effective for treating atherosclerosis with methods that minimize complications and hasten recovery.

Although a number of techniques and instruments currently used in minimally invasive therapy were proposed years ago, the ability to make the transition from science fiction to reality required the maturation of enabling technologies. Similarly, advances in computer, communications, robotics, and display technologies have enabled the development of telepresence surgery.[3]

The fundamental principle of a telepresence surgery system is to extend a surgeon's psychomotor skills and problem-solving abilities to a remote environment. The goal of telepresence technology is to project a surgeon's manual dexterity to a remote location while providing real-time tactile and visual feedback from the location to the surgeon.[4] Unlike telerobotic surgery, in which a robotic manipulator is directed by preprogrammed computer instructions, or surgical virtual reality,[5] in which manipulations are

From the Department of Surgery, Uniformed Services University of the Health Sciences, Bethesda (Drs. Bowersox and Cordts); the Medical Technology Laboratory, SRI International, Inc., Menlo Park; and the Department of Surgery, Tripler Army Medical Center, Honolulu (Dr. Cordts).

Supported in part by the National Institutes of Health (GM 44902) and by the Advanced Research Projects Agency (DAMD 17-95-I-5019).

When this work was performed, Mr. Jensen, Mr. Green, and Drs. Hill and Shah were employees of SRI International, the nonprofit research institute that developed the telepresence surgery system described. No authors have a commercial or other financial interest in this work.

Presented at the Forty-ninth Annual Meeting of the Society for Vascular Surgery, New Orleans, La., June 11-12, 1995.

Reprint requests: Jon C. Bowersox, MD, PhD, 109 Brookside Drive, Portola Valley, CA 94028.

24/6/69714

performed in a simulated environment, telepresence is a unique human-machine technology that directly and transparently projects a surgeon's motions to a remote location.[6]

The potential applications of telepresence surgery are myriad. It would allow surgeons to perform surgery in patients who are in hazardous environments or who have been victims of biologic or chemical warfare agents. Surgical procedures could be safely performed during prolonged radiographic imaging. It could provide surgical expertise in situations in which an experienced surgeon is not available, such as enabling life-saving trauma surgery in rural settings or on a battlefield. Telepresence surgery could also be used to provide expert assistance to trained surgeons who are performing difficult or unusual procedures in a community hospital and are unable or unwilling to transfer a patient to a tertiary care center.

We describe the first studies of the use of telepresence surgery on live animals. We have demonstrated the technical feasibility of remote tissue handling by performing tissue incision, dissection, and blood vessel suturing completely by telepresence surgery.

MATERIALS AND METHODS

Telepresence surgery system. The telepresence surgery system used in these studies was developed by SRI International. It is a unique modular system that comprises a surgeon's workstation and a remote surgical unit (RSU) (Fig. 1). The workstation provides a full-color stereoscopic (3D) image of the operative field projected in real-time full-frame video. Beneath the imaging screen are two surgical instrument handles that are grasped by the surgeon. The ergonomic design is such that a completely natural orientation of operative field and hand position are attained. Alsoincluded are stereophonic audio input, a microphone for communicating with the RSU, and video displays of the remote operating room.

The RSU is positioned over the operating table at a location removed from the workstation. The only physical connection between the two units is an electronic data cable, which could be replaced by a wireless communications link. The RSU has two high-resolution digital videocameras with electronic zoom lenses oriented to provide 3D image transmission. Beneath the cameras are servomotor-controlled manipulator arms with interchangeable surgical instrument attachments on their ends.

Degrees of freedom (DOF) refers to the number of different ways that a robotic arm can move. The human arm has 7 DOF, and the human hand has over 20 DOF.[7] In the current telepresence surgery system, the manipulators have 4 DOF, plus opening and closing of the actuators (the surgical instruments attached to the manipulators) (Fig. 2). Thus the surgeon operates as though his or her wrist were immobilized. The movements of the surgeon's hands at the workstation are precisely and instantly translated to movement of the instruments at the ends of the manipulator arms of the RSU. Instruments currently available include a scalpel handle, needle holders, curved and blunt graspers, and fine scissors.

An essential component of the telepresence surgery system is force reflection, the built-in tactile feedback provided to the surgeon at the workstation.[8] Each movement made by the surgeon at the workstation is resisted by the tissue in contact with the surgical instruments on the RSU. The resistance is proportional to the force applied and the characteristics of the tissue manipulated. For example, when grasping and retracting a tissue, the sense of resistance to stretch is instantly felt by the surgeon at the workstation, which allows him or her to reduce the force of grasping to prevent tearing. This sensation is similar to that achieved during tissue manipulation in conventional open surgery and is essential for precise atraumatic handling of tissues. Because it reproduces the normal tactile input, surgery with the telepresence surgery system feels natural and intuitive to surgeons.

Ex vivo studies. Three-cm incisions were made anteriorly in fresh excised segments of bovine aorta. Conventional techniques were used to close the arteriotomies with continuous running suture of 4-0 polypropylene or Gore-tex (W.L. Gore and Associates; Flagstaff, Ariz.). Tapered-point needles were used.

Telepresence closure of arteriotomies were performed by a surgeon at the workstation. Assistance was limited to suture-cutting by a nonphysician assistant located at the RSU. A suture was placed in the operative field by the surgical assistant, after which all tissue manipulation was performed by the surgeon at the workstation. All procedures were recorded in real time on videotape. One of the stereoscopic cameras on the RSU was used for recording telepresence surgical procedures, and a scene camera was used for conventional procedures.

Time-and-motion analysis was conducted by a complete review of all videotapes by the senior clinical author (JCB). Times for suture placement (start of needle entry into tissue until removal from tissue at the end of the bite), positioning (needle

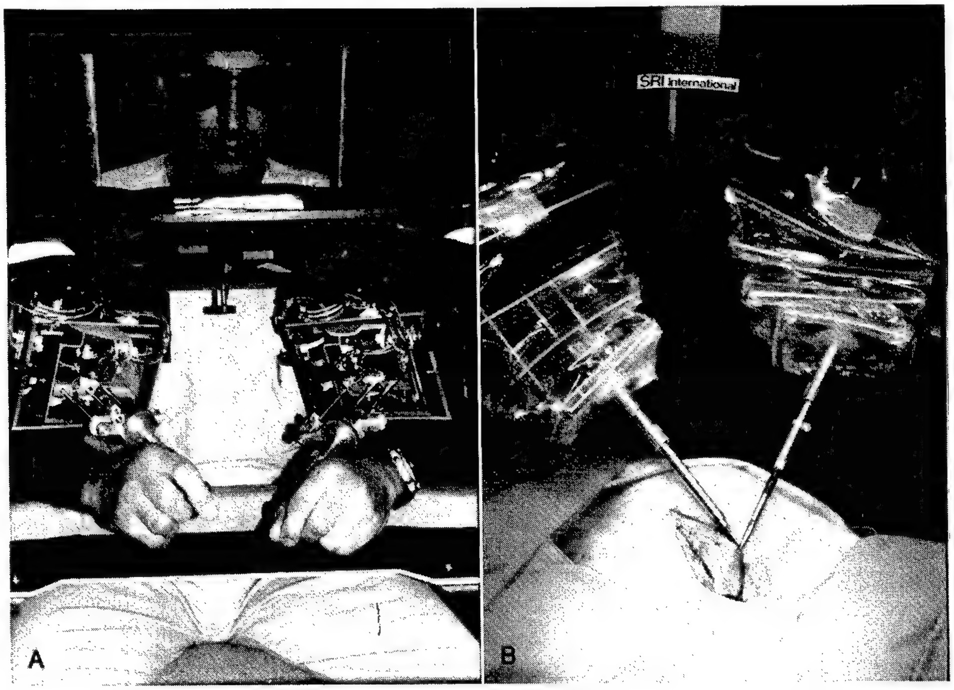


Fig. 1. Telepresence surgery system. **A,** Surgeon's workstation with 3D viewing screen and instrument handles. **B,** RSU with manipulator arms.

removal from tissue to start of next bite), and knot tying were recorded.

In vivo studies. All animal care complied with the "Principles of Laboratory Animal Care" (formulated by the National Society for Medical Research), and the *Guide for the Care and Use of Laboratory Animals* (NIH Publication No. 86-23, revised 1985). General anesthetic was used in female swine weighing 35 to 50 kg. Noninvasive cardiac, respiratory, and blood pressure monitoring was performed throughout the course of the experiments.

Common femoral arteries were exposed and isolated by the telepresence surgeon, and 100 U/kg heparin was administered intravenously. After the surgeon occluded the femoral artery by applying traction to vessel loops, a 3-cm arteriotomy was made. 6-0 polypropylene or polytetrafluoroethylene (PTFE) suture on a tapered needle was used to close the arteriotomy in a continuous running suture. As in ex vivo experiments, assistance was limited to cutting suture. At the completion of the arteriotomy closure, clamps were removed. Hemostasis was achieved with topical Gelfoam (Upjohn, Kalamazoo, Mich.) or fibrin adhesive (American Red Cross, Rockville, Md.) held in place for 2 minutes by the surgeon working through the telepresence surgery system. Patency was confirmed by continuous-wave Doppler insonation conducted immediately after and 1 hour after repair and by transecting the femoral artery distal to the repair at the completion of the study and observing pulsatile blood flow. Repaired arterial segments were then excised and opened. The presence of thrombus and the integrity of the suture line were noted.

RESULTS

Ex vivo experiments. Conventional closure of a 3-cm arteriotomy, including knot tying at the beginning and end of the suture line, required 192 ± 24 sec (n = 4). Arteriotomy closure performed with the telepresence surgery system required 483 ± 118 sec (n = 9). All procedures by either technique were technically acceptable as assessed by integrity to pressure perfusion, patency, and intraluminal evaluation of the suture line.

With conventional techniques, 79% of the time was spent placing sutures and 21% tying knots. With telepresence surgery, 76% of time was spent placing sutures and 24% tying knots. Telepresence surgery required more time for grasping and repositioning the needle between each suture than did conventional suturing.

Eliminating force feedback (tactile sensation) and 3D imaging resulted in a 16% to 20% mean increase

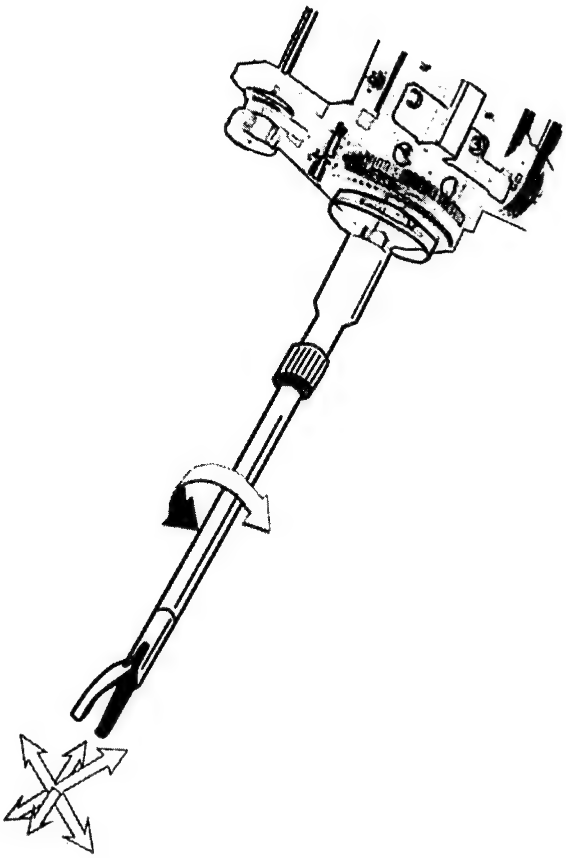


Fig. 2. DOF describe the planes in which manipulator arms can be moved. 4 DOF plus actuator (instrument tip) opening and closing are available in the current telepresence surgery system.

in the time required to complete the procedure with telepresence surgery, although the technical quality was comparable in each case. Subjectively, lack of force feedback and 3D imaging eliminated the intuitive sensation and increased operator fatigue. This was most noticeable when working on small-diameter vessels, in which the ability to complete procedures was severely compromised.

Other ex vivo procedures performed with bovine aortae were patch angioplasty with a 0.4-mm PTFE cardiovascular patch (n = 4) and end-to-side PTFE patch to aorta anastomosis performed with 6-mm thin-walled PTFE (n = 4). The procedures were completed with telepresence surgery with technically acceptable results. That the RSU manipulator had only 4 DOF required rotation of the aorta to complete the procedures—a limitation that would be overcome with additional manipulator DOF.

In vivo femoral artery repair. With a continuous suture, 2-cm lacerations in common femoral arteries were closed successfully by telepresence surgery with the starting suture placed in a mattressed fashion. Arteriotomy closure required 1388 ± 122 sec (n = 6) with the telepresence surgery system. All closures performed by telepresence surgery were technically adequate, patent, and without suture-line bleeding. In no instance did excessive tension result in a tear in the blood vessel or a break in the suture.

DISCUSSION

More than 4 decades ago, harnessing atomic energy required methods for safely handling dangerous amounts of radioactive materials. Separating nuclear workers from contaminated environments was first accomplished by creating mechanical links to manipulate tools used in hazardous spaces.[9] This method was effective for very specific tasks over short distances and is occasionally used today. True remote manipulation, or teleoperation, was developed to handle large items that were physically remote from the operator. These manipulator systems were cumbersome and relied only on visual input to the operator. Although they were effective for handling large objects in tasks that required only moderate accuracy, the lack of tactile feedback hindered the ability to precisely position small objects or perform intricate tasks.[10]

Telepresence manipulators provided tactile sensory input to the operator by providing force feedback, which is a sense of resistance encountered by the manipulator arms when contacting objects in the remote environment. Force feedback resulted in more rapid and accurate task completion and decreased operator fatigue. With force feedback, tasks that required greater precision could be performed.[11,12]

In the 1970s, the National Aeronautics and Space Administration began developing telepresence systems for surgery in space.[13] The anticipated construction and operation of a manned space station required contingency planning for emergency surgical care in a location where specialists would be unavailable. Although the spacestation was never built, the potential of remote telepresence surgery in a broad spectrum of applications was recognized. Continued research and the maturation of necessary supporting technologies facilitated the development of a complete integrated system that could be used in preclinical studies. Our goal was to demonstrate the

feasibility of using a telepresence surgery system to perform common procedures that require the cognitive and motor skills of a trained surgeon. The dissection, handling, and suturing of tissue are tasks common to all surgical disciplines. Vascular anastomoses and the closure of small-vessel arteriotomies require psychomotor integration of basic skills and represent reasonable clinical criteria for judging the system's effectiveness. On the basis of these criteria, telepresence surgery was successful. In remote or battlefield applications of telepresence surgery, a nonphysician assistant would be trained to assist the telepresence surgeon. For this reason, assistance during our studies was limited to technical skills that a surgical technician is currently trained to provide. These skills include tissue grasping, suture cutting, and retraction.

A primary objective in designing complex systems that require operator control or input is creating an ideal human interface. The ideal interface is one that feels completely natural, or intuitive, to the user.[14] Laparoscopic surgery is not natural because the eye–hand axis normally used in surgery and everyday tasks is disrupted. Instead of looking down at his or her hands while working, the laparoscopic surgeon is forced to look up at a screen, disrupting normal oculovestibular sensory input.[15] A further limitation of laparoscopic surgery is the use of long instruments with the fulcrum located at the abdominal wall, far from the tissues being manipulated. Tactile feedback is lost, and precise tissue manipulation is more difficult. Consequently, laparoscopic surgical skills need to be learned and reinforced by regular practice.

We found the telepresence surgery system to be remarkably similar to conventional surgery. No special training was conducted before using the system, and the time required for suturing and tying did not decrease substantially with use. Subjective comments about how closely telepresence techniques resembled conventional techniques add further support to this contention. Almost invariably a surgeon using the telepresence system would at some point remove a hand from the instrument handle and attempt to retract tissue as if the operative field was right there. The successful closure of arteriotomies in 2- to 3-mm diameter vessels demonstrated the feasibility of telepresence surgery in a procedure that requires a high degree of integration of technical skills. We believe that the longer times required for task completion by telepresence surgery reflect the reduced DOF available in the current system and the limitations imposed by the current selection of instruments. The needle holders and forceps used were larger than optimal for fine vascular suturing, which made needle grasping and knot tying more difficult. Vascular instruments are currently being adapted for use with the telepresence surgery system.

Stereoscopic vision and force reflection contributed to the intuitive interface. The observation that simple suturing could be performed without either feature with only a modest increase in task-completion times most likely reflects the ability of the human visual system to use alternative sources of depth information when stereoscopic vision is lost. Other cues, including perspective, interposition, contrast, object size, and shadows become of primary importance.[8] Of equal significance is that procedures became tedious and fatigue developed quickly. Suturing of small vessels was so difficult as to be impractical. Further studies of visual and tactile cues are required to define the optimal user interface.[16]

The current telepresence surgery system has only four DOF in the manipulator arms. Thus the potential range of instrument movements simulates a human arm with a fused (nonmobile) wrist. Although the system is adequate for demonstrating feasibility, wrist function will need to be added for it to achieve widespread acceptance in clinical use. The next-generation system will provide a full 7 DOF in the manipulator arms. With this addition, a surgeon will be capable of performing virtually all hand movements used in the operating room.

The obvious uses of telepresence surgery are in the extension of the expertise of a surgeon to locations not currently possible. In the military, hemorrhage is the primary cause of death on the battlefield. Most casualties exsanguinate within 30 minutes of wounding.[17,18] Although it is impossible to have enough surgeons on the front lines in battle, it is feasible to have an RSU accompanying the medics who first encounter wounded soldiers. These medics will have the training to provide surgical assistance and perform paramedic skills, including intubation and initiation of intravenous access. Parallel development programs are exploring methods for providing anesthetic support to distant locations with remote monitoring, artificial intelligence, and new drugs. Skilled surgeons operating from established field hospitals or even from the United States could rapidly perform life-saving stabilizing surgery. Telepresence surgery could help provide the first

reduction in early battlefield mortality in more than 150 years.

Another unique application of telepresence systems is the performance of emergency surgery in an hazardous environment or on a casualty contaminated by biologic or chemical warfare agents. With such systems, the current limitations imposed by chemical protective suits or the delays imposed by patient decontamination could be overcome. Removing unexploded munitions from body cavities is another potential use with both military and civilian applications.[19]

Advanced telepresence surgery systems could be used in minimally invasive surgery and would return the instrument fulcrum and dexterity to the tissue level. This would facilitate vascular anastomoses through small trocar incisions and permit some procedures now done by conventional techniques to be performed lessinvasively.[20]

Because all hand and manipulator movements are digitally processed, force-reduction algorithms can be introduced that would allow movements of a surgeon's hands to be scaled down at the tissue level. Thus a 10-mm hand excursion by the surgeon could be translated to 0.1 mm or even less at the tissue level. Microvascular procedures could be performed on a level that is not possible with conventional techniques. The same approach could be used to dampen incorrect movements or tremors, which would allow novice, aging, nervous, fatigued, or less-dexterous surgeons to perform vascular procedures.[21]

Telepresence surgery systems will require further evolution and testing before they extend a surgeon's reach to a remote operating room. Most important in the development process is a sound clinical foundation. By demonstrating that fundamental procedures in vascular surgery can be performed by a remotely located surgeon, we have taken the first steps to acquiring a revolutionary new tool for the 21st century surgeon.

The assistance of Lawrence W. Way, MD, and the Experimental Surgery Laboratory of the University of California, San Francisco is gratefully acknowledged.

Technical details of the SRI Telepresence Surgery System and videotapes of procedures performed are available from the Medical Technology Laboratory, SRI International, 333 Ravenswood Drive, Menlo Park, CA 94025.

REFERENCES

1. Donahue JH. Laparoscopic surgical procedures. Mayo Clin Proc 1994;69:758-62.
2. Soper NJ, Brunt LM, Kerbl K. Laparoscopic general surgery. N Engl J Med 1994;330:409-19.
3. Green PS, Piantanida TA, Hill JW, et al. Telepresence dexterous procedures in a virtual operating field [abstract]. Am Surg 1992;57:92.
4. Sheridan TB. Defining our terms. Presence: Teleoperators and Virtual Environments 1992;1:272-74.
5. Durlach NI, Mavor AS, editors. Virtual reality: scientific and technical challenges. Washington, DC: National Academy Press, 1995.
6. Thring MW. Robots and telechirs. New York: Wiley & Sons, 1983:275-8.
7. Tendick F, Mori T, Way LW. Future of laparoscopic surgery. In: Way LW, Bhoyrul S, Mori T, editors. Fundamentals of laparoscopic surgery. New York: Churchill Livingstone, 1995:235-52.
8. Draper JV. Human factors in telemanipulation: perspectives from the Oak Ridge National Laboratory experience. In: Kim WS, editor. Proceedings on telemanipulator technology and space telerobotics. Vol. 2057. Boston: SPIE, 1993:162-74.
9. Goertz R. Philosophy and development of telemanipulators. Argonne, Ill.: Argonne National Laboratory, 1951.
10. Flatau CR. The manipulator as a means of extending our dexterous capabilities to larger and smaller scales. In: Transactions of the American Nuclear Society 21st conference on remote systems technology. La Grange, Ill.: American Nuclear Society, 1973:19-22.
11. Hill JW. Study of modeling and evaluation of remote manipulation tasks with force feedback. Final report no. 7696, JPL contract 95-5170. Menlo Park, CA: SRI International, 1979.
12. Bejczy AK. Sensors, controls, and man-machine interface for advanced teleoperation. Science 1980;208:1327-35.
13. Rasor NS, Spickler JW. Endocorporeal surgery using remote manipulators. In: Herr E, editor. Remotely manned systems: exploration and operation in space. Pasadena, Calif.: California Institute of Technology, 1973:483-92.
14. Rosenberg LB. Virtual fixtures as tools to enhance operator performance in telepresence environments. In: Kim WS, editor. Proceedings on telemanipulator technology and space robotics. Vol. 2057. Boston: SPIE, 1993:10-21.
15. Satava RM, Ellis SR. Human interface technology: an essential tool for the modern surgeon. Surg Endosc 1994;8:817-20.
16. Davis P, Martelli S, Sabatini AM. An experimental setup for investigating sensor-based teleoperated surgery procedures. IEEE Trans Biomed Eng 1990;12:1942-3.
17. Bellamy RF. The causes of death in conventional land warfare: implications for combat casualty care research. Mil Med 1984;149:55-62.
18. Zajtchuk R, Sullivan GR. Battlefield trauma care: focus on advanced technology. Mil Med 1995;160:1-7.
19. Fackler ML. Potential danger to operating room personnel when an unexploded "Devastator] bullet is being removed. J Trauma 1989;29:703-4.
20. Jones DB, Rubin BG, Olin JM, et al. Laparoscopic-assisted aortofemoral bypass [abstract]. Surg Endosc 1995;9:234.
21. Charles S, Williams RE, Hamel B. Design of a surgeon-machine interface for teleoperated microsurgery. IEEE Trans Biomed Eng 1989;11:883-4.

Submitted June 15, 1995; accepted October 5, 1995.

DISCUSSION

Dr. Sushil K. Gupta (Framingham, Mass.). I congratulate Dr. Bowersox for reaching an important milestone in a journey that began two decades ago—a journey to perform surgery in space by remote control.

The goals of this project are noble—to operate on patients in distant locations or hazardous environments. I do not want to belittle the authors' significant achievement to date by asking them simple questions such as who will prep and drape the patient, who will administer anesthetic, and who will then care for the patient. It is a significant achievement to be able to tie a 6-0 polypropylene suture with a remotely controlled robotic device. I can't even get our residents to do this without breaking or entangling the suture while I'm standing at the table.

I empathize with fellow members in the audience who are wondering: With the radiologists encroaching on our business on one end and now robots appearing at the other end, isn't it time to retire?

Dr. Bowersox will acknowledge, however, that significant challenges are still ahead. I have some performance concerns. Is there any lag time now with the current system tethered at 600 feet and only 4 DOF in the robotic arm? What will happen to the bandwidth and throughput when you go wireless and add 7 DOF and better optics? Are there plans to add head-mounted motion systems to simulate head movement to look in deeper or fix the posterior wall injury that is all too common? Would it not increase the digital communication requirements such that it would prevent real-time surgery? In a recent experiment, the network control of teleoperators not too far away had significant lag times of 50 msec to several seconds, which makes some tasks impossible to carry out.

I also disagree with the authors' contention that this approach could be used to dampen incorrect movement or tremors, allowing novice, aging, nervous, or less-dexterous surgeons to perform vascular procedures. I do agree that further development of this kind will greatly enhance the field of minimally invasive surgery and allow vascular surgeons to perform some procedures with laparoscopic techniques by improvements in the vision and the instrumentation to carry out more delicate tasks.

Dr. Bowersox. Thank you for your insightful review and pertinent questions. I'd like to emphasize from the start that the telepresence surgery program is one small component of a larger program sponsored by the Advanced Research Projects Agency and supported by the National Institutes of Health in Advanced Technology in all areas of biomedicine, and I think that information will provide the answers with regard to how this system is going to integrate with the access to anesthetic and to physiologic monitoring.

Once again, I'm a clinician and not a computer scientist or engineer, but I'd like to briefly review some of the questions you raised about the technical issues of the system. Lag time is certainly an issue when you deal with satellite communications. Rudimentary studies have shown that if you introduce more than 100 msec of lag time, it is very difficult to do surgery with accuracy and precision. This difficulty does not occur if you remain in a fiberoptic environment or even over a microwave link. So the quick answer to that question is it can be done with current technology at distances up to but not including satellite links. We can go across country or even across a continent with fiberoptic communications. A solution is underway with software development that will allow this connection to go over a satellite link, although probably not for the next several years.

The 4 DOF is a limitation; it's currently as though you were operating with a fused wrist. A prototype of a manipulator with 7 DOF has been built and should be ready for testing by the end of 1995. This prototype will allow all motions of the human arm to be modeled and should remove the limitation imposed by having only four DOF.

The bandwidth requirements are modest. From a technical perspective, 45 megabits/sec should provide the bandwidth necessary for this system. Interestingly, most of that requirement is for the stereo video, which can be accommodated by current fiberoptic networks with no compression. That the bandwidth is not a limitation surprised me when I first started working on the system. The actual manipulator and tactile feedback occupies a very small portion of that bandwidth, only 1 megabit/sec, which won't increase substantially when going to 4 DOF.

The head-mounted display is a very intriguing concept; we're testing it now in the laboratory. Will this have a role for the aging, disabled, or tremulous surgeon? I'm not sure, but I do know that this system could be used to overcome those limitations, and I think it's something that we as clinicians need to explore and make a decision about.

Proc. ANS Sixth Annual Topical Meeting on Robotics and Remote Systems
Monterey, California, Vol. 2, pp 713-720, February 5-10, 1995.

TWO-HANDED TELEPRESENCE SURGERY DEMONSTRATION SYSTEM

John W. Hill	Joel F. Jensen	Philip S. Green	Ajit S. Shah
SRI International	SRI International	SRI International	SRI International
Menlo Park, CA 94080	Menlo Park, CA 94080	Menlo Park, CA 94080	Menlo Park, CA 94080
(415) 859-5085; fax 859-2658	(415) 859-3911; fax 859-2658	(415) 859-2882; fax 859-2658	(415) 859-4904; fax 859-2658
john_hill@qm.sri.com	joel_jensen@qm.sri.com	philip_green@qm.sri.com	ajit_shah@qm.sri.com

ABSTRACT

Endoscopic surgical methods are replacing open surgery in many procedures, but dexterity and force feedback are not adequate with current tools. To enhance the ability of surgeons to operate endoscopically, we have developed a telepresence system with integrated 3D stereo viewing, a prototype force-reflecting manipulator, and aural feedback. Careful attention was paid to the human factors in the endoscopic surgery setting to make the system natural to use in the hope of eliminating the long training period normally required. The 4-axis (plus gripper) manipulator provides the same degrees of freedom as the lap aroscopic tools now being used for surgery. The bilateral control system provides for magnified motion and/ or force reflection. This approach eliminates the motion reversal, or fulcrum effect, in operating through the abdominal wall. Preliminary dexterity experiments with different force feedback and viewing conditions verify intuitive use and fast learning. Recent developments with dexterous, two-handed operation are reported.

I. INTRODUCTION

During the past several years, laparoscopic surgery has largely replaced conventional open surgery for removal of the gallbladder and has begun to make inroads into other procedures as well. However, the dexterity and touch sensitivity that laparoscopic instruments provide are quite poor compared to those of open surgery, because the instruments are operated through an incision in the abdominal wall which serves as a fulcrum, with the surgeon's hand on the opposite side of the fulcrum, away from the surgical site. Moreover, the video image engenders a feeling of disconnectedness. Consequently, every motion is deliberate rather than intuitive, and relatively simple maneuvers, such as suturing, are time consuming and frustrating.

In an effort to enhance the ability of surgeons to operate laparoscopically, we have developed a telepresence surgery system with integrated stereo viewing, force-reflecting manipulators, and aural feedback.[1-8] This remote surgery system provides the surgeon with the sense that the surgical instruments are actually in his or her hand. When applied to laparoscopic surgery, it provides the sense of doing *open* surgery. To accomplish these improvements, careful attention was paid to the human factors involved in surgery and to the special demands of laparoscopic surgery.

The new telepresence demonstration system incorporates two manipulators, each with the same four degrees of freedom (plus tip actuation) used in laparoscopic instruments now in use. However, with telepresence, the surgeon's hand is effectively on the *correct* side of the fulcrum. The bilateral control system provides for magnified motion and/or force reflection. The low-inertia electro-mechanical design provides a high-bandwidth, low-drag system with surprising realism. System operation is intuitive and natural; no operator training is required and remote tasks can be performed with a high degree of dexterity. Preliminary dexterity experiments have been conducted with various force feedback and viewing conditions.

II. BACKGROUND

Robots have begun to find applications in surgery in recent years.[9] For example, placement of probes in the brain, eye, and spinal cord has been demonstrated using industrial robots such as the Unimation Puma 260. Typically, the robot inserts a needle along its axis deep into a tumor. The Robodoc[a] orthopaedic surgery system,[10] developed at IBM and Integrated Surgical Systems,

[a] All product names mentioned in this document are the trademarks of their respective holders.

produces a precise cavity in the femur for hip replacement. Transurethral resection of the prostate (TURP) has been performed robotically.[11]

In contrast to robot automation, others have envisioned the potential advantages of telemanipulation in surgery. Alexander[12] shows a concept for a teleoperator surgery system in which the operator could see and feels what he is operating on. Thring[13] describes a bilateral surgical telerobot concept in which exoskeletal masters would be used to operate a pair of xyz Cartesian manipulators.

Marsuhima and Koyanagi[14] describe a hand-held master with a tool-like portion, and Sabatini, Bergamasco, and Dario[15] describe cutting with a finger-sized manipulator (4 links) proposed for corneal transplant surgery. Gayed et al.[16] and Guerrouad and Vidal[17] have described the use of a sterotaxic manipulator with a remote center of rotation, for placing a probe into the eye. They used a six-axis manipulator with joystick controls that lacked force feedback. Charles et al.[18] describe the human-interface requirements for microsurgical telerobot surgery.

With the increasing use of laparoscopic surgical techniques, there is now a strong need for telemanipulators that can perform the full spectrum of surgical maneuvers, e.g., cutting, suturing, dissecting, normally performed by surgeons. Instruments with the required dexterity, speed, and delicate force feedback have not been previously developed, nor has a methodology for making their use natural and effective.

III. TECHNICAL APPROACH

A. SRI Telepresence System

Our current demonstration system, diagrammed in Figure 1, consists of two modules: the Operator Module and the Worksite Module. The operator module, as shown in Figure 2, provides a pair of force-reflecting hand controllers and a stereo display system with adjustable magnification. Typically, we use a field of view of about 10 cm by 14 cm, twice the size of the video field in the worksite module; however, much greater magnification is possible. The operator module contains a color monitor, a Tektronix liquid-crystal shutter for stereographic viewing (the operator wears passive polarized glasses), a mirror to create a "virtual workspace" beneath the hand-operated master controller, stereo speakers, and the master, which is outfitted with a surgical instrument handle.

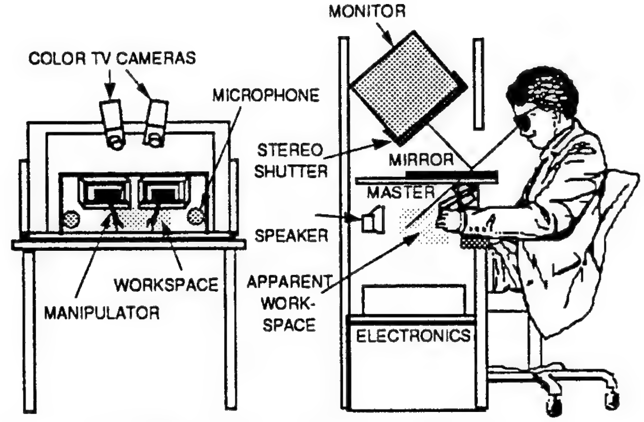


Figure 1. SRI Telepresence Surgery System

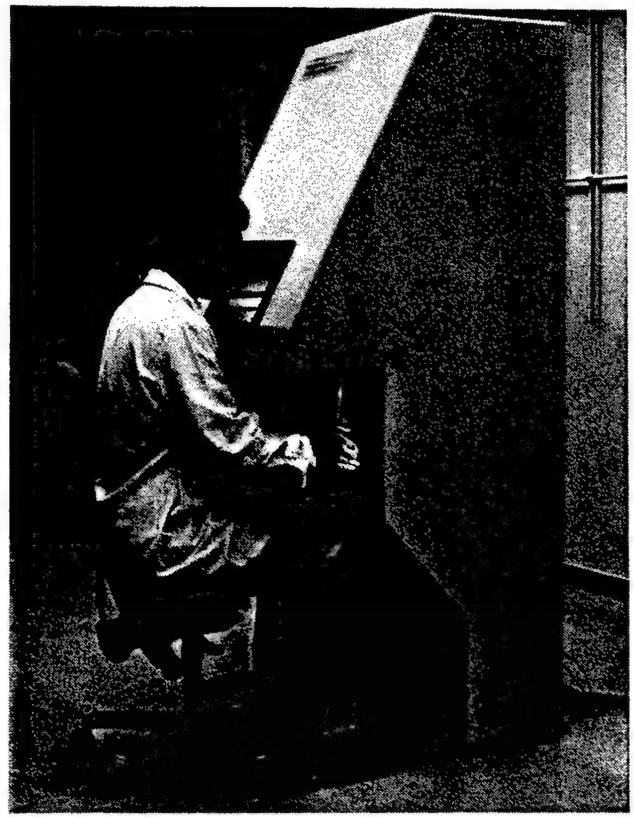


Figure 2. Operator Module

The worksite module, shown in Figure 3, provides stereopsis with two color CCD video cameras separated by about 10°, the same interocular viewing disparity that we experience with a visual field 40 cm in front of us.

Also included are a force reflecting manipulator with surgical instrument tips and two microphones.

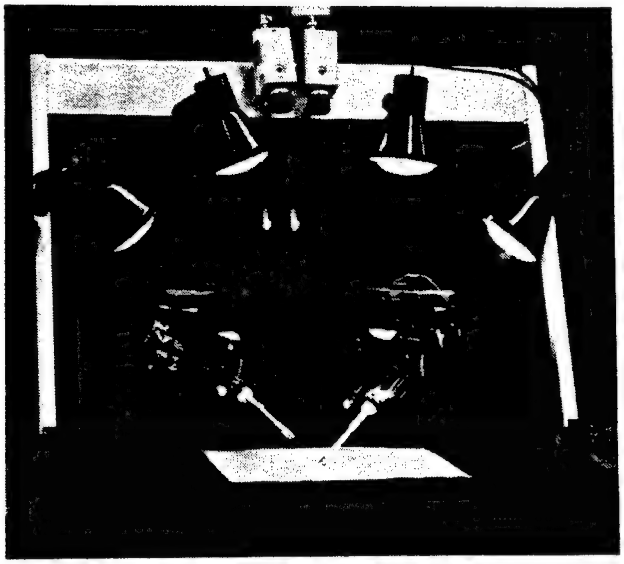


Figure 3. Worksite Module

B. Telepresence Human Factors

The master and slave manipulators are placed in juxtaposition to the camera and to the display respectively so as to be geometrically identical. Our purpose is to effectively transport the remote site back to the operator in such a way as to create the illusion that he or she is reaching and looking directly into it. This results in natural and spontaneous control motions by the operator.

Telepresence is a unique method of remote manipulation. The telepresence surgeon grasps surgical instrument handles, looks down into a three-dimensional surgical field, reaches into the field with the instruments, and operates. He sees the tips of the instruments move with his hands as they manipulate the tissues, and feels the tissues resist. To the surgeon, this looks and feels like the conventional open surgery he/she has already trained and practiced on. The patient could be in the same room or 100 kilometers (60 miles) away: it makes no difference. Telepresence provides such a compelling sense of reality that the surgeon is drawn immediately into the work, with no sensation of remote control. Hand motions are quick and precise. Furthermore, the visual field, instrument motion, and force feedback can be scaled up or down; for example, to make microsurgery even easier than it would be if the surgeon were at the patient's side, operating directly.

C. Force-Reflecting Manipulators

One master, or system controller, is shown in Figure 4. The handgrips consist of the loop handles of a pair of surgical forceps. An extension joint supports the handles, which in turn is supported by a three-axis gimbal, providing free rotation on its three angles. The loop handles extend and retract along its linear extension axis and open and close. Small electric motors attached to each axis by miniature timing belts reflect magnified forces from the slave manipulator back to the instrument handle in the operator's hand, allowing multiaxial forces on the manipulator to be perceived in a completely natural way. Each slave (surgical manipulator) is a similar articulated device, shown in Figure 5.

By keeping the mechanism very light and the motors centrally located, we have minimized the inertia of the system felt by the operator. We have also minimized friction by using few stages of gearing, low friction/low inertia actuators, and low friction bearings throughout. The usual drawbacks of inertia and friction—reduced operator performance and fatigue after prolonged usage—have been largely eliminated.

Force feedback is provided on all axes of the manipulator, including the gripper squeeze force. Forces and torques generated as the tool touches objects in the course of its work are reproduced with great fidelity at the operator's hand. Soft objects feel soft; hard ones hard. The constraints of sliding, inserting, and bottoming out are clear

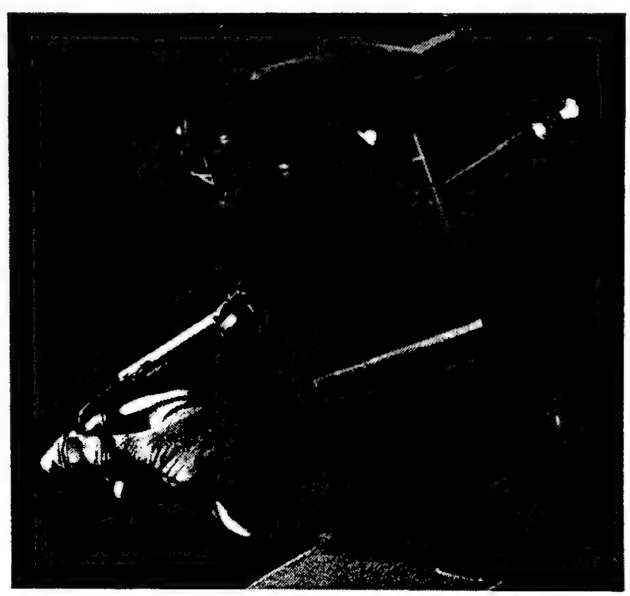


Figure 4. Master Hand Control

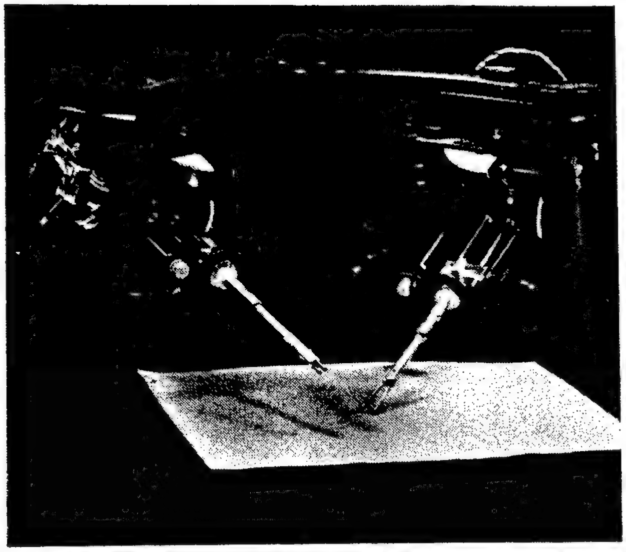


Figure 5. Slave Manipulator

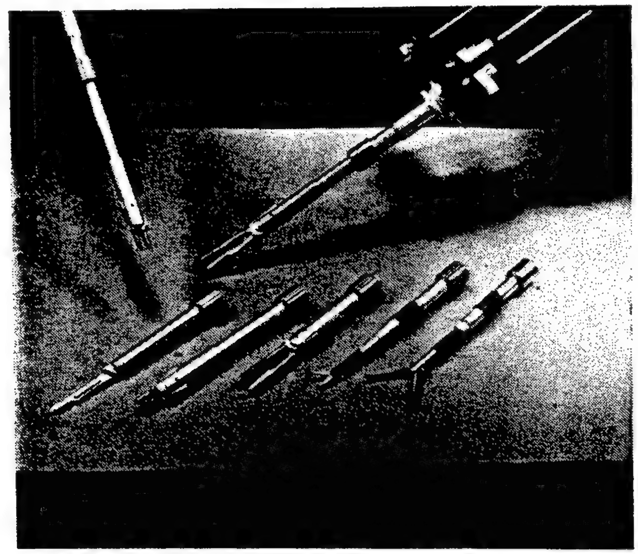


Figure 6. Medical End Effectors

and natural. This will be important in surgery; currently used laparoscopic surgical instruments lack adequate force sensitivity.

The following performance of the manipulator has been obtained.

- Frequency response (natural frequency) exceeds 20 Hz on all axes (the human limit is about 10 Hz.)
- Force levels of 7 N (approximately 1.5 pounds) can be applied continuously in any direction.
- Friction is limited to 0.3 N (approximately 1 ounce) with the master-slave loop closed.

D. Interchangeable End-Effectors

A family of interchangeable surgical end effectors are provided, including graspers, needle drivers, scalpels, and scissors, as shown in Figure 6. The tool tips are adapted from actual surgical instruments and are driven via a push rod in the center of the connecting rod attaching the tool tips to the manipulator. To obtain high grasping forces on the needle holder end effector, we employ a tool with short, carbide inset jaws. Gripping forces of between 50 to 100 N (10 to 20 lb) are obtained for good grasp on the needle. The scalpel, which may be outfitted with standard surgical blades, is not actuated by the grip mechanism.

Interchangeability is obtained by a collet near the middle portion of the end-effector connecting rod. A clamp nut is unscrewed a few turns, and the collet frees the outer connecting rod. A ball and socket, easily separated, link the inner push rod. Tools can be changed in a few seconds.

E. Manipulator Control System

The control system for the manipulator is shown in Figure 7. This is basically a position and velocity (PV) control system similar to that employed by Goertz[19] in early work, with bilateral manipulators for handling radioactive materials.

The control system is entirely digital; it faithfully reproduces hand motion and reflects forces to the operators hand. Motion and force feedback can be scaled to suit the task at hand. Dynamic gravity compensation is provided, making the tool feel weightless.

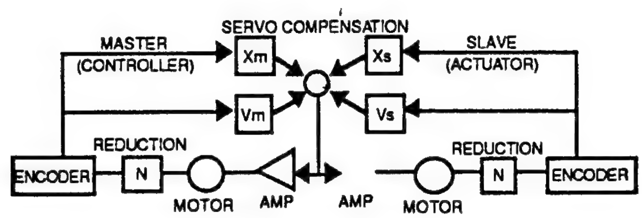


Figure 7. Manipulator Control Diagram

F. Stereographic Visualization

The imaging subsystem is shown in Figure 8. Two standard NTSC video cameras provide the stereoscopic image pair. A Datacube dual, digital frame buffer alternately provides each image to the operator's display, a Tektronix frame-sequential stereo system with a 120 frame/s TV monitor and a synchronously switched polarizing filter. The operator wears passive, polarized glasses, which pass alternate frames to the left and right eye respectively. The doubled frame-rate ensures flicker-free stereo.

G. Aural Feedback System

The current worksite module incorporates two microphones positioned above and to the sides of the worksite itself. Two speakers are located in the operator module just above and to the sides of the hand-controller region—the *apparent* worksite. This arrangement provides stereophonic sounds that seem to emanate from the worksite and that are generally associated with the side of the worksite from which they originated. The distance between the left and right microphone elements is approximately the same as the distance between the speakers that reproduce the sound.

III. PERFORMANCE EVALUATION: ONE-HANDED OPERATION

We have conducted informal performance tests to assess the capabilities of the telepresence system using only one hand. It is remarkably easy to perform tasks without practice by merely grasping the instrument handle (the master) and doing them. With the assistance of an assistant holding or tensioning tissue, we have demonstrated surgical dissection of both excised animal muscle and organ tissue, using the scalpel end effector. With the grasper, we have demonstrated free-needle threading, suturing—including anastomosis (surgical resection) of pig intestine—and blunt dissection.

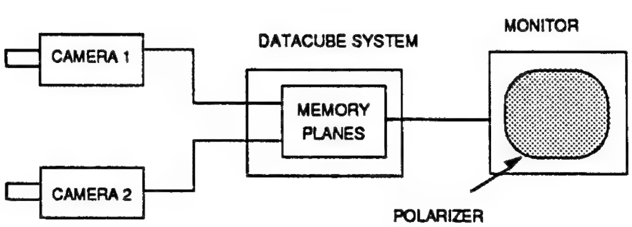


Figure 8. 120-Hz (field-rate) Stereographic Display System

A. Experimental Design

We have also conducted preliminary psychophysical experiments with different manipulation tasks and viewing conditions to compare telepresence with both free-hand and conventional laparoscopic surgical manipulation. Three subjects (two engineers and a surgeon with laparoscopic training) were involved. Completion time was measured for:

- Bead Transfer—Pick-and-place transferring of 0.25-inch OD/0.125-inch ID beads (cut sections of plastic tubing) from pins spaced approximately 1.00 inch apart. This is a positioning task. Three beads were transferred.

- Cannulization—Insertion of a 1.00-inch length of 0.125 OD semi-rigid plastic tubing into a slit in the side of 0.125 ID soft latex tubing. This is both a positioning and orientation task that simulates surgical cannulization of a vessel or duct with a catheter.

Four manipulation conditions were investigated:

- Free-Hand—Using a hemostat held directly by the test subject. Viewing was with the unaided eye. This simulates open surgery.

- Laparoscopic, 2D—Using a laparoscopic grasper (approx. 12 inches long) pivoted through a rubber sheet 5 inches above the task (simulating the abdominal wall). Viewing was through a video camera about 50 inches away, zoomed to give a 4-inch field of view across the monitor at the subject's eye level. This simulates laparoscopic surgery, except that it minimizes depth cues because of the 50-inch viewing distance.

- Telepresence System, 3D—Using the SRI telepresence system with the grasper end effector. Viewing was stereoscopic, also zoomed to give a 4-inch field of view across the monitor. This simulates open telepresence surgery.

- Telepresence System, 2D—Using the SRI telepresence system, except viewed only with the left camera.

B. Procedure

Each subject started the series on a different manipulation test. This balanced the effect of practice over the conditions. The whole series took less than one hour. The subject was allowed to practice the task once, then was timed on the next three successive performances. If the subject dropped a bead or tube, it was replaced by the experimenter. Errors were not counted. A stopwatch was used to measure the task time.

C. Results

The results are shown in Figures 9 and 10. Generally, the performance of all three subjects was similar; cannulization took about twice as long as the transfer. Free-hand was the fastest condition, with telepresence 3D taking about twice as long. Telepresence 2D took about 20% longer than telepresence 3D. With the laparoscope 2D, tasks took about 7 times as long for bead transfer and 15 times as long for tube cannulization.

IV. PERFORMANCE EVALUATION: TWO-HANDED OPERATION

We have also conducted informal performance tests to assess the capabilities of the two-handed telepresence system in performing telesurgery. With two hands, assistance in tensioning and positioning tissue is not required. We have demonstrated the following capabilities with a high level of dexterity:

- Two-handed manipulation using graspers to stretch and dissect tissue, locate and clamp a bleeding artery, and explore a pig abdomen (examining intestine, liver, spleen, etc. for damage and remove foreign bodies).

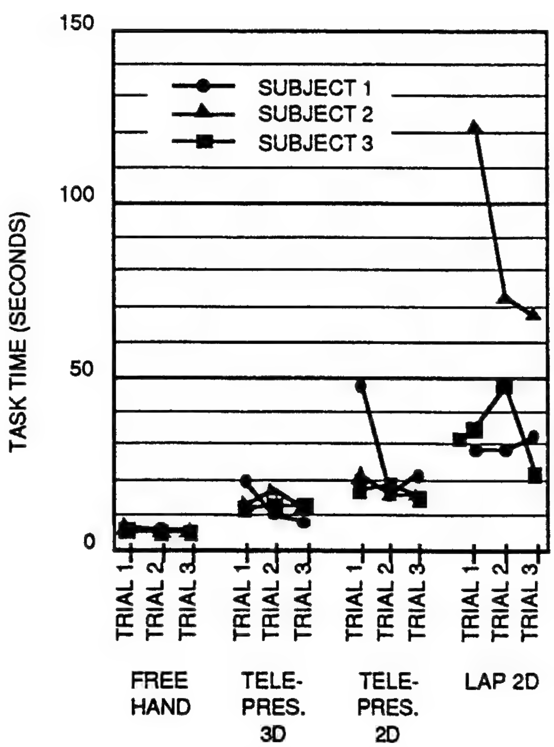


Figure 9. Results of the Bead-Transfer Task

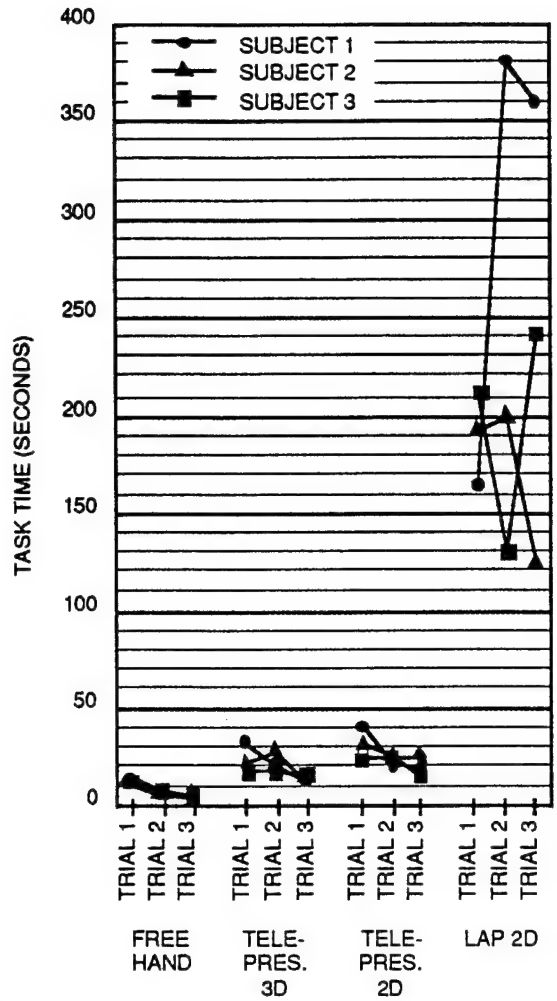


Figure 10. Results of the Cannulization Task

- Unaided surgical dissection in excised animal organ tissue, using the scalpel end effector in one hand and a surgical grasper in the other.
- Unaided surgical dissection using the micro scissors end effector in one hand and a surgical grasper in the other.
- Tying knots in suture materials using the instrument-tie technique.
- Tying a square knot in suture materials using the normal method with two hands.
- Suturing-including anastomosis (surgical resection) of pig intestine using a needle holder and a grasper employing both individually tied sutures and running or "purse string" sutures.

We have not yet conducted time and motion studies of these new capabilities. Generally, performance with the manipulators is somewhat slower than with hand-held instruments, "free-hand condition." Performance with the manipulators is much faster than with laparoscopic surgery techniques. Laparoscopic suturing, which can be only haltingly accomplished by the most dedicated surgeons after many hours of practice, can be accomplished immediately by an untrained operator using the telepresence system.

V. CONCLUSIONS

As a result of the care we have taken to make the telepresence system duplicate the operator's direct visual, tactile, and aural experience, we have developed an effective system remote manipulation environment with a compelling sense of realism. The image of the slave as seen by the operator is congruent with the master, and the slave manipulator is seen to move in the direction the operator commands by hand motion.

As evidenced by these experimental results, the telepresence system has proved much more effective than conventional laparoscopic technique and is close to the performance of free-hand (open surgery). A laparoscopic version of the telepresence system is under development and is expected to bring to laparoscopic surgery the same dexterity that it has demonstrated for remote open surgery.

VI. REFERENCES

1. P. GREEN, "Remote Minimally Invasive Surgery—Product and Business Opportunities," presented at a *Surgical-Business Satellite Meeting of the Society of American Gastrointestinal Surgeons (SAGES)*, Arlington, Virginia (1992).

2. P. GREEN, R. SATAVA, J. HILL, and I. SIMON, "Telepresence: Advanced Teleoperator Technology for Enhanced Minimally Invasive Surgery," *Society of American Gastrointestinal Surgeons*, Washington, DC (April, 1992). This paper was also presented at *Medicine Meets Virtual Reality*, San Diego, California (1992).

3. P. GREEN, "Virtual Reality and Telepresence in Internal Medicine," *American Society for Artificial Internal Organs*, Nashville, Tennessee (1992).

4. R. SATAVA, "Surgery 2001: A Technology Framework for the Future," *Society of American Gastrointestinal Surgeons* (SAGES), Washington, DC (1992).

5. P. GREEN, "Minimally Invasive Telepresence Surgery," *San Francisco Surgical Society*, San Francisco, California (1992).

6. R. SATAVA, "Telepresence: Endoscopy in the Year 2000," *American Association of Gynecological Laparoscopists*, Illinois (1992).

7. JOHN W. HILL, PHILIP S. GREEN, JOEL F. JENSEN, and AJIT S. SHAH, "Telepresence Surgery Demonstration System," *Proc. IEEE Conference on Robotics and Automation*, San Diego, California, Vol. 3 p. 2302-2307 (1994).

8. I. SIMON, "Virtual Reality, Robotics, and Surgery in the 21st Century." Presented at the *Society for Urology and Engineering at the American Urological Association*, San Antonio, Texas (1993).

9. B. PREISING, T. C. HSIA, and B. MITTELSTADT, "A Literature Review: Robots in Medicine," *Proc. IEEE Engineering in Medicine and Biology*, 0739-5175/91/ 0600-13, pp. 13-22 (1991).

10. RUSSELL H. TAYLOR et. al., "An Image-Directed Robotic System for Precise Orthopaedic Surgery," *IEEE Transactions on Robotics and Automation*, **10** (3), 261-275 (1994).

11. W. S. NG, B. L. DAVIES, R. D. HIBBERD, and A. G. TIMONEY, "Robotic Surgery: A First-Hand Experience in Transurethral Resection of the Prostate," *Proc. IEEE Engineering in Medicine and Biology*, pp. 120-125 (1993).

12. A. D. ALEXANDER, "Impacts of Telemation on Modern Society" *First IFToMM Symposium*, Vol. 2, p. 122 (1978).

13. M. W. THRING, *Robots and Telechirs*, Ellis Horwood Ltd. (1983).

14. K. MARSUHIMA and H. KOYANAGI, "Servo micromanipulator 'Tiny-Micro Mk. I'," *Fourth CISM-IFToMM Symposium*, p. 251 (1981).

15. M. SABATINI, M. BERGAMASCO, and P. DARIO, "Force Feedback-Based Telemicromanipulation for Robot Surgery on Soft Tissues," *Proc. IEEE Engineering in Medicine and Biology, 11th Annual Int. Conf.*, p. 890-891 (1989).

16. M. BEN. GAYED, et. al. "An Advanced Control Manipulator for Surgical Applications," *Systems Science*, Vol. 13, p. 123-134 (1987).

17. A. GUERROUAD and P. VIDAL, "SMOS: Stereo-telemanipulator for Ocular Surgery" *Proc. IEEE Engineering in Medicine and Biology, 11th Annual Int. Conf.*, p. 879-880 (1989).

18. STEVE CHARLES, ROY E. WILLIAMS, and BILL HAMEL, "Design of a Surgeon-Machine Interface for Teleoperated Microsurgery," *Proc. IEEE Engineering in Medicine and Biology, 11th Annual Int. Conf.*, p. 883-884 (1989).

19. RAY GOERTZ, et al., "ANL Mark E4A Electric Master-Slave Manipulator," *Proc. 14th Conf. on Remote Systems Technology*, p. 115-123 (1966).

ACKNOWLEDGMENTS

This work was supported in part by SRI International and in part by the National Institutes of Health, under Grant No. GM 44902, and by the Advanced Research Projects Agency (ARPA) under contract N000014-94-C-0040.

The authors would like to acknowledge the assistance of Lynn Smolik, M.D. (Veterans Administration Medical Center, Palo Alto, California) in developing the manipulation tasks and participating in the performance evaluation of the telepresence system in one-handed mode.

SECOND ANNUAL INTERNATIONAL
SYMPOSIUM ON

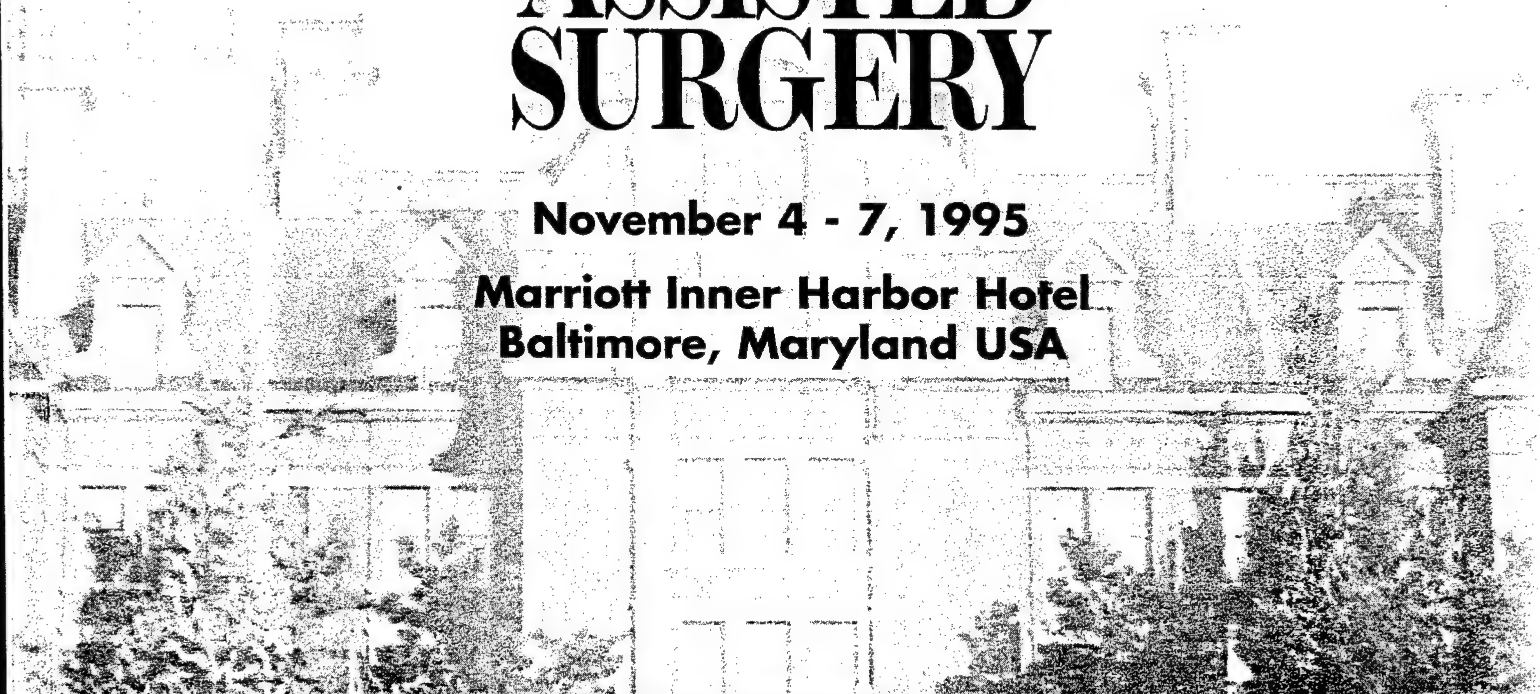
MEDICAL ROBOTICS

and

COMPUTER ASSISTED SURGERY

November 4 - 7, 1995

Marriott Inner Harbor Hotel
Baltimore, Maryland USA



MRCAS '95

SPONSORED BY THE JOHNS HOPKINS INSTITUTIONS, SHADYSIDE HOSPITAL AND CARNEGIE MELLON UNIVERSITY

TECHNICAL CO-SPONSOR: IEEE ROBOTICS AND AUTOMATION SOCIETY
IEEE ENGINEERING IN MEDICINE AND BIOLOGY SOCIETY

MOBILE TELEPRESENCE SURGERY

P.S. Green, J.F. Jensen, J.W. Hill, and A. Shah
SRI International, Menlo Park, California 94025

E-mail: philip_green@qm.sri.com; joel_jensen@qm.sri.com; john_hill@qm.sri.com; ajit_shah@qm.sri.com

Key words: Telepresence surgery, combat surgery, laparoscopic, telemedicine, telemanipulator

Categories: Active and passive robotic manipulators for medicine; Precision, accuracy and validation for medical robotics; Augmented reality in surgery; Telesurgery and telemedicine

BACKGROUND

The Telepresence Surgery System developed by SRI International has been previously described.[1-6] It is intended for three distinct applications: (1) telesurgery, wherein the surgeon may participate in operations performed at remote sites; (2) minimally invasive surgery, especially, laparoscopic surgery—telepresence makes it look and feel like open surgery; and (3) microsurgery, in which the surgeon's dexterity is enhanced through scaling of the image, the motions, and the force feedback.

In this paper we report on recent improvements to the remote-surgery version of the system and especially on its adaptation for mobile telesurgery on the battlefield.

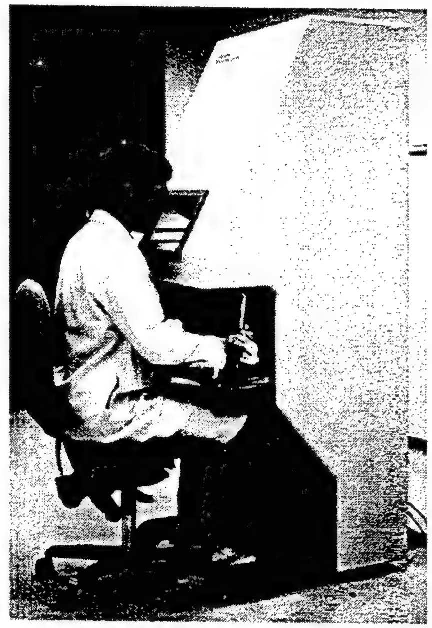


Fig. 1. The latest surgeon's console provides two hand-control masters with surgical-instrument handles, a stereographic view into the surgical site, and a microphone and speakers for communicating with the surgical assistant or nurse in the operating room. Looking straight ahead, the surgeon sees a panoramic view across the remote surgical table, on three side-by-side LCDs.

THE TELEPRESENCE SURGERY SYSTEM

SRI's Telepresence Surgery System consists of two main modules: a surgeon's console, shown in Fig. 1, and a remote surgical unit (RSU), located at the surgical table and shown in Fig. 2. The surgeon sits at the console and looks down into the surgical field, a "virtual workspace" recreated by a special arrangement of a 120-field/s stereographic video monitor with a liquid-crystal shutter

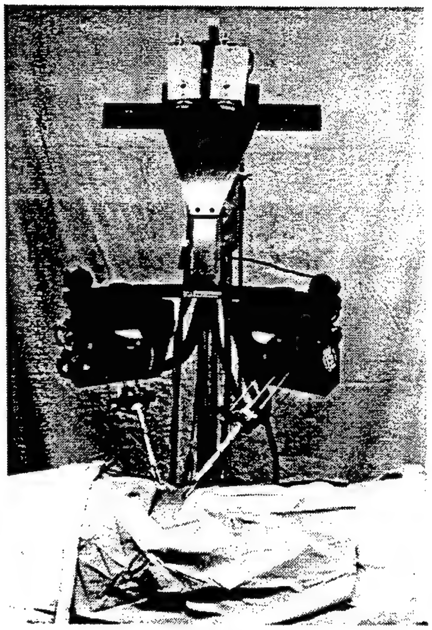


Fig. 2. The remote surgical unit (RSU) comprises two slave manipulators with interchangeable surgical instruments, two video cameras positioned correctly with respect to the manipulators and canted in for stereo convergence in the middle of the operating field, microphones, and a trio of video cameras (not shown) that produce a panoramic view of the operating room from the surgeon's perspective.

(the operator wears passive polarized glasses) and a mirror. In the open-surgery version of the system, described here, the stereographic video is generated by a pair of video cameras on the RSU; they are positioned over the patient in special relationship to the surgical manipulators, as described below.

The surgeon reaches under the mirror and grasps two surgical-instrument handles that operate two master manipulators, each of which directs the movement of a slave manipulator at the RSU by means of a highly responsive, force-reflecting servo-controller. Affixed to the ends of the manipulator arms are interchangeable surgical instruments—forceps, needle drivers, bowel graspers, scalpels, and cautery tips. As shown in Fig. 3. the surgeon sees the instruments in the stereographic image—they appear to be emerging from the handles in his hands. When he moves his hand controls, the instruments move as if they were rigidly attached to the controls. When the instruments touch the tissue or tug on a suture, that force is reflected back through the instrument handles in a realistic manner. Sounds from the instruments and the surgical assistant's voice are picked up by stereo microphones and relayed to speakers in the surgeon's console. To the surgeon, it looks, it feels, and it sounds as if he is performing the task directly on the patient, with conventional surgical instruments. The strength of this perception enables the surgeon to carry out complex tasks with quick, precise motions.

The masters and slaves are lightweight, responsive, well-balanced, and gravity-compensated. Friction has been minimized by reducing the stages of gearing, using low-friction/low-inertia actuators, and using low-friction bearings throughout. Thus, the usual drawbacks of inertia and friction—degraded operator performance and fatigue after prolonged use—have been largely eliminated. The bilateral control system provides for scaled motion and force reflection, which, along with scaled video, enable the surgeon to perform microsurgery with normal hand motions. The current open-surgery manipulators have five degrees of freedom, with force feedback in each axis (including opening and closing the jaws of graspers or scissors). More dexterous manipulators and a wider assortment of easily interchanged surgical instruments are

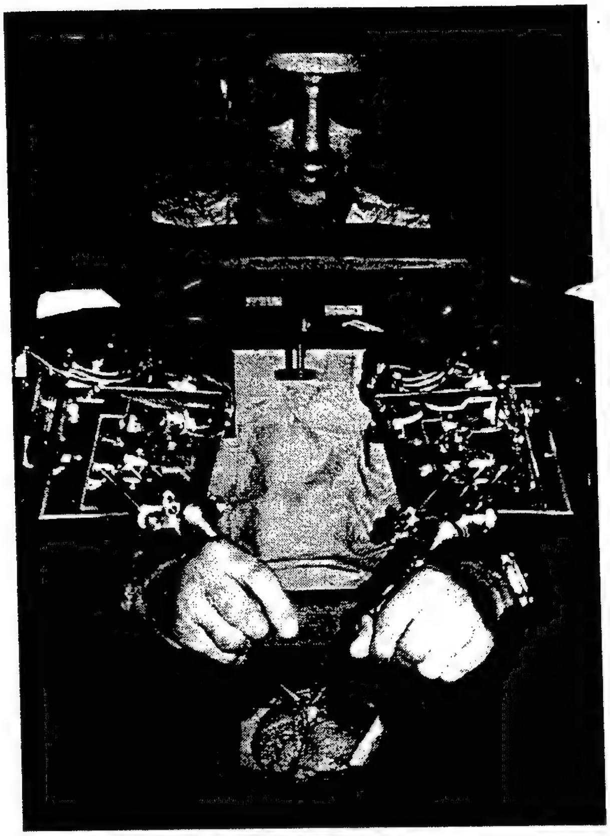


Fig. 3. As illustrated in this superposition, the surgeon sees the instruments in the stereographic image—they appear to be emerging from the handles in his hands and they move in exact synchronization with his hand movements. To the surgeon, it looks, it feels, and it sounds as if he is performing the task directly on the patient, with familiar surgical instruments. Responsive, force-reflecting servos enable the surgeon to operate quickly and confidently.

being incorporated into a new version of the system, now under development.

A laparoscopic version of the RSU, not described here, employs very different remote manipulators, designed especially for operation through cannulas. A stereo laparoscope is substituted for the camera pair.

REMOTE SURGERY ON THE BATTLEFIELD

Potentially, telepresence surgery can make a significant contribution to the management of combat trauma. Nine out of ten combat-related deaths from nonfatal injuries occur in the combat zone prior to evacuation, the majority from loss of blood. Many of these lives could be saved if surgical treatment were available within one hour of injury—referred to as the "Golden Hour." However, in modern warfare, the front line may move forward so quickly that mobile army surgical hospitals (MASH units) cannot be established close enough to the combat zone to be effective. Currently, the only care available to the seriously wounded soldier within the combat zone is that provided by the field medic, whose goal is to stabilize the victim and prepare him for evacuation. Sending combat-ready trauma surgeons into the combat zone is now being given serious consideration; it is a very unattractive prospect, one which we hope will be made unnecessary by the advent of telepresence surgery.[7]

To provide surgical services in the zone of combat, SRI is developing a battlefield version of its Telepresence Surgery System. This version has been installed in a mobile surgical vehicle, dubbed the *medical emergency forward area surgical telepresence* (MEDFAST), envisioned to be deployed as illustrated in Fig. 4. After first aid has been administered by the medic, the wounded soldier in need of immediate surgery is brought to the MEDFAST and put on

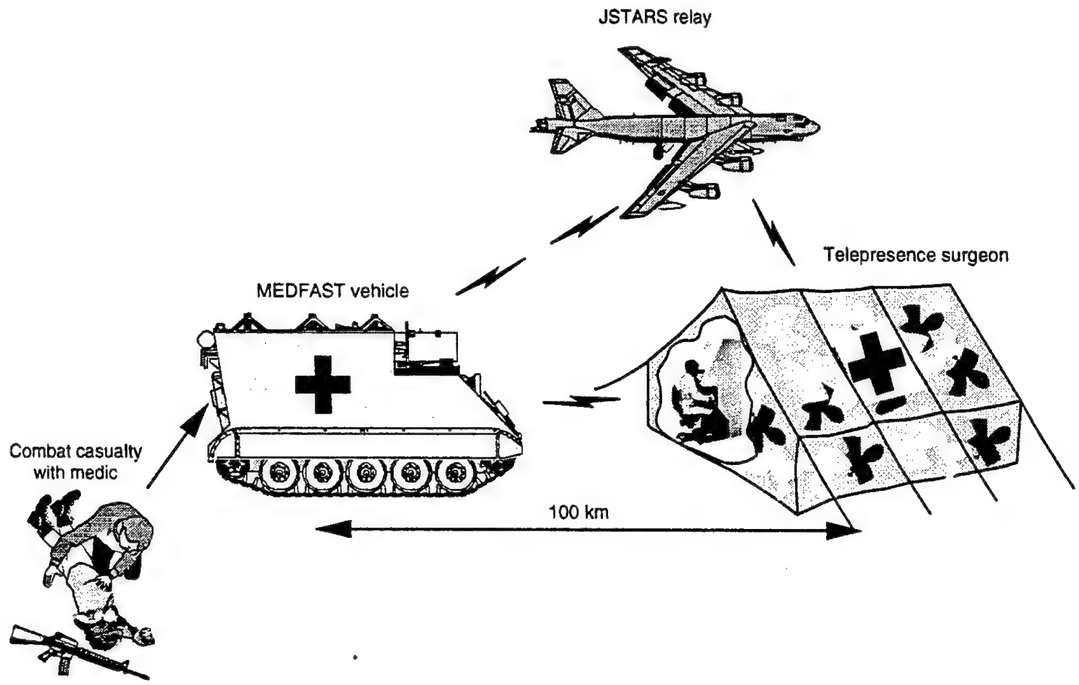


Fig. 4. From a position safely behind the lines, the telepresence combat surgeon of the future will carry out surgeries in mobile surgical vehicles operating throughout the zone of combat, with the assistance of medics assigned to each vehicle. First field tests will employ a point-to-point microwave link to carry video, servo, audio, and patient monitoring information, which eventually may be relayed by low-earth-orbit satellites.

the operating table. The telepresence combat surgeon carries out only a limited spectrum of procedures. These are primarily for stabilizing wounded soldiers, so that they can be evacuated when conditions permit, and for treating conditions that, if deferred, would seriously affect recovery. The most threatening conditions are airway obstructions, sucking chest wounds, and profuse bleeding. Working hand in hand with the medic, the surgeon can remotely explore for and repair injuries to major vessels and abdominal and pelvic organs, remove bone fragments and foreign material, and debride damaged tissues. The wound can then be packed and dressed; wound closure is left to the next echelon of care. Thus, telepresence surgery greatly augments the trauma care that the medic alone can provide.

This concept was first demonstrated in June 1993 during a medical field exercise held at Ft. Gordon in Augusta, GA. In a tent, Army surgeons, seated at an early version of our console operated on an "injured soldier"—actually, a life-like mannequin with pig intestines in its abdominal cavity. A medic at the patient's side assisted the surgeon. The patient, the RSU, and the medic were located in a transportable operating room (OR) 30 meters from the tent. Cables carried the control, video, and audio signals between the units (a high-bandwidth, two-way radio link would be required in an actual combat situation). At Ft. Gordon, only a single master-slave combination was used; nevertheless, the potential was evident and the surgeons were enthusiastic.

Encouraged by the Ft. Gordon results, we began preparation for a much more realistic demonstration, in which surgery would be carried out in a combat-ready vehicle outfitted as a mobile OR. The new OR is in an XM577A3 tracked, armored vehicle, shown in Fig. 5, which has been equipped with a special operating table, an electrically controlled gantry for positioning the RSU over the patient, and patient monitoring equipment.

The new surgeon's console (Figs. 1 and 3) was constructed and outfitted.[8] This version incorporates two hand-control masters; the earlier version had only one. In addition, it has improved stereographic video, a microphone and speakers for communicating with the medic, surgical assistant, or nurse in the OR, and three side-by-side liquid crystal displays (LCDs) that provide a panoramic view across the operating table. The telesurgeon looking up from the surgical wound sees the medic's face and any activity in the OR from the same perspective he or she would have had if standing at tableside.

This equipment was transported to Washington, D.C., in October 1994, and demonstrated at the annual convention of the Association of the U.S. Army (subsequent demonstrations in Washington were made in April and May 1995). Still linked by a cable, the two units were situated 160 meters apart—the 577 in the hotel parking lot and the surgeon's console in a third-floor exhibition hall. On the operating table lay a soldier mannequin with lacerated pig intestines and liver in its

Photo courtesy of FMC Defense Systems

(a)

(b)

Fig. 5. Operating room in a tracked, armored vehicle. (a) The XM577A3 Armored Tactical Command and Control System vehicle, which was modified for this project by Foster-Miller Corp., (b) Interior of the 577, showing the operating table, surgical manipulators, cameras and lights, the medic, and auxiliary surgical and support equipment. The "patient" was a dummy with pig intestines, shrapnel, and a simulated bleeding artery in its abdominal cavity.

abdominal cavity, along with bits of shrapnel, and a simulated bleeding artery squirting blood (activated surreptitiously by the medic). This is representative of the type of abdominal wound suffered in combat.[9]

Surgeons, and many others, have now had the opportunity to sit at the console, expose and examine the injured organs, suture lacerations, remove shrapnel, and expose the "bleeder," which the medic then clamped. Surgeon and medic worked together as if they were standing across the table from each other. For example, the medic would pass the suture to the surgeon and then provide countertension on the tissues while the surgeon sewed. Surgeons were able to run suture lines and do instrument ties with high dexterity and speed.

The general consensus was that the feasibility of telepresence surgery on the battlefield had been demonstrated, although a number of improvements were needed. Preparation has begun for actual field trials of the system. Three notable features are being added: (1) a pair of seven-degree-of-freedom hand controls and manipulators, (2) a broader array of surgeon-interchangeable instruments, and (3) a wireless communication system.

COMMENTS AND CONCLUSIONS

SRI has established that precise surgical procedures can be carried out with telepresence. We believe that within the next decade telepresence surgery will become an established component of a new, technologically enhanced mode of cost-effective health care delivery. Because of the substantial medical and financial benefit that telepresence will bring to laparoscopic and other minimally invasive procedures, its first routine use is expected to be within the individual hospital and surgical center. Subsequently, remote surgery also will become practical. We have demonstrated telepresence surgical procedures, including a wide variety of procedures in live-animal studies [10], over 160 meters of copper wire. We are now working toward demonstrating animal surgeries over a much greater distance using a microwave link. Highly reliable fiber optic links will be readily available for civilian telesurgery. Mobile telepresence surgical equipment may prove especially effective for trauma care, not only under combat conditions but for civilian disaster intervention as well.

ACKNOWLEDGMENTS

This work was supported in part by SRI International and in part by the National Institutes of Health under Grant No. GM 44902; by the Advanced Research Projects Agency (ARPA) under Contract N00014-94-C-0040, P.O. number 32858 from Assurance Technology Corp. (Government Contract N00014-93-D-2022), and Grant DAMD17-95-I-5019; and by the U.S. Army Medical Research Acquisition Activity under Grant No. DAMD17-95-1-5019. The 577 vehicle was equipped as an operation theatre by Foster Miller, Inc. in cooperation with United Defense. The views represented in this article are those of the authors and do not reflect the official policy of the Department of Defense or the U.S. Government (approved for public release, distribution unlimited).

REFERENCES

[1] R. Satava, "Surgery 2001: A technology framework for the future," *Soc. Am. Gastrointestinal Surgeons* (SAGES), Washington, DC, 1992.

[2] P. Green, R. Satava, J. Hill, and I. Simon: "Telepresence: advanced teleoperator technology for enhanced minimally invasive surgery," *Soc. Am. Gastrointestinal Surgeons*, Washington, DC, April 1992. This paper was also presented at *Medicine Meets Virtual Reality*, San Diego, CA, 1992.

[3] R. Satava: "Telepresence: endoscopy in the year 2000," *Am. Assoc. Gynecological Laparoscopists*, Chicago, IL, 1992.

[4] I. Simon: "Virtual reality, robotics, and surgery in the 21st century," *Soc. Urology and Engng. at the Am. Urological Assoc.*, San Antonio, TX, 1993.

[5] G. Taubes: "Surgery in cyberspace," *Discover*, pp. 84-94, Dec. 1994.

[6] J. Hill, P. Green, J. Jensen, and A. Shah: "Telepresence surgery demonstration system," *Proc. IEEE Conf. Robotics and Automation*, San Diego, CA, Vol. 3, pp. 2302-2307, 1994.

[7] R.F. Bellamy and R. Zajtchuck, eds: *Textbook of Military Surgery*, Off. Surg. Gen., USA, 1991.

[8] J. Hill, J. Jensen, P. Green, and A. Shah: "Two-handed telepresence surgery demonstration system," *6th Topical Meeting on Robotics and Remote Systems*, Monterey, CA, 5-10 Feb. 1995.

[9] T.E. Bowen and R.F. Bellamy: *Emergency War Surgery*, U.S. Gov't. Printing Off., 1988.

[10] J. Bowersox, A. Shah, J. Jensen, J. Hill, and P. Green: "Applications of a telepresence surgery system in vascular surgery," presented at the Spring 1995 meeting, *Soc. Vascular Surgery.*

Health Care in the Information Age
H. Sieburg, S. Weghorst, and K. Morgan (Eds.)
IOS Press and Ohmsha, 1996

COMPLEX TASK PERFORMANCE IN CYBERSPACE: SURGICAL PROCEDURES IN A TELEPRESENCE ENVIRONMENT

Jon C. Bowersox, M.D., Ph.D.,[1,2] Anthony J. LaPorta, M.D.,[3]

Paul R. Cordts, M.D.,[4] Sunil Bhoyrul,[5] Ajit Shah, Ph.D.[1]

[1]SRI International, 333 Ravenswood Avenue, Menlo Park, CA 94025

[2]Department of Surgery, Stanford University School of Medicine, Stanford, CA

[3]Department of Surgery, Fitzsimmons Army Medical Center, Aurora, CO

[4]Department of Surgery, Tripler Army Medical Center, Honolulu, HI

[5]Department of Surgery, University of California, San Francisco, CA

ABSTRACT

To assess the capabilities of our fully functional, prototype telepresence surgery system, experienced surgeons performed complete operative procedures on live, anesthetized pigs. Cholecystectomy, the prototypical procedure for evaluating the integration of surgical skills, was successfully performed in six animals. There were no

aborted attempts or complications. Other procedures completed included gastrotomy and enterotomy closures, anastomosis of the small intestine, and nephrectomy. No specific training was required for using the telepresence surgery system, and the "feel" of the system was described as intuitive. Operative times were longer than required in conventional, open surgery, most likely the result of the four degrees of freedom available in the manipulators of the current-generation system. Force feedback and high-resolution, stereoscopic video input facilitated performance. Surgeons operating through a first-generation telepresence system can achieve technical results equivalent to those obtained in conventional surgery.

BACKGROUND

Telepresence surgery is based on the premise that an immersive sensory environment can substitute for the physical presence of a patient.[1] It presumes that high-fidelity visual, auditory, and tactile input can be electronically transmitted to a surgeon in such a way that he or she can use that input to make the same decisions that would be made in an operating room. Furthermore, telepresence surgery requires the accurate replication of a surgeon's hand motions at the remote site where the patient is located.

The basic concepts of telepresence surgery have been demonstrated with a prototype telepresence surgery system developed by SRI International.[2,3] In tests on inanimate models and isolated tissues, tissue incision, cannulation, suturing, and knot tying were all successfully completed. Tests of these psychomotor performance skills, although indicative of the precision and accuracy that are possible with the prototype system, do not adequately assess whether a complete operative procedure could be performed by telepresence surgery.

The operative phase of surgery requires tissue incision, retraction and exposure, dissection, cutting, grasping, suturing, and knot tying. The sequence of steps required for a procedure is usually the same from one patient to the next, but each individual has unique anatomic characteristics. Further variability is introduced by disease processes that cause tissue distortion. Thus, real-time feedback of visual and tactile information to the operating surgeon is critical for the safe and accurate performance of surgery. Consequently, to assess the actual potential of telepresence surgery, we performed complete operations on live, anesthetized swine.

METHODS

The telepresence surgery system used in these studies has been previously described. A surgeon sits at a console equipped with stereoscopic video input, and controls master manipulators that provide force feedback. The remote surgical unit where the patient is located has slave manipulators with five degrees of freedom, including instrument opening and closing. Standard surgical instruments are available to the surgeon (Figure 1). For the experiments reported in this study, the surgeon's console and remote surgical unit were located in the same surgical suite, connected by electronic cables.

The surgeon's perception is one of presence at the operative field, providing the potential to perform procedures with the precision and accuracy obtained if the surgeon were physically present at the operating table.

All animal care complied with the Principles of Laboratory Animal Care (formulated by the National Society for Medical Research) and *Guide for the Care and Use of Laboratory Animals* (NIH Publication No. 86-23, revised 1985). Female Hampshire swine (n=4) were anesthetized by standard techniques and monitored throughout the course of the experiments. At the completion of the procedures, the anesthetized animals were euthanized with an overdose of barbiturates.

A midline laparotomy was performed and retractors placed. All subsequent procedures were performed using the telepresence surgery system. A fully trained general surgeon operated from the control console, assisted by a nonphysician technician at the remote location with the animal. All procedures initiated were successfully completed using the telepresence surgery system, including cholecystectomy, gastrotomy and enterotomy closures (to simulated stomach and intestinal injuries, respectively), repair of liver laceration, and nephrectomy. The infrarenal abdominal aorta was exposed and a 1-cm segment was excised. An interposition graft of 6 mm polytetrafluoroethylene (PTFE) (Gore-Tex, a product of WL Gore & Associates, Inc., Flagstaff, AZ) was placed. In addition, the telepresence surgery system was used to incise groin skin, perform dissection and exposure of the common femoral artery, and isolate the vessels. A 3-cm long arteriotomy, simulating arterial injury, was closed by means of the telepresence surgery system.[4]

Before the creation of liver lacerations or simulated vascular injuries, the animals were systematically anticoagulated with sodium heparin, 100 U/kg, administered intravenously.

Performance measures included time to task completion, quality of the completed procedure, and system limitations noted. For arterial repairs, vessel patency and suture line integrity were assessed.

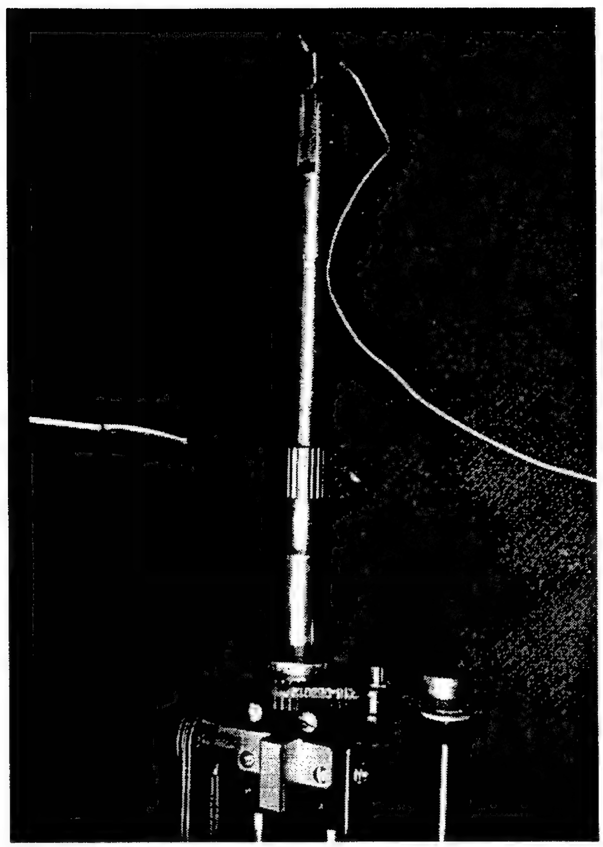


Figure 1a. Slave manipulator arm equipped with a needle holder

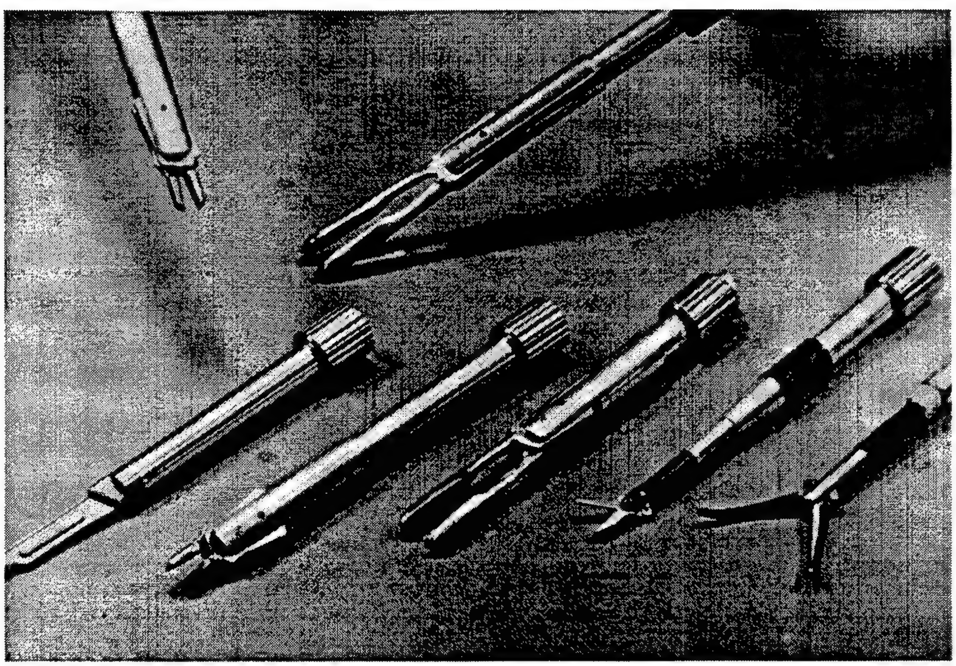


Figure 1b. Range of surgical instruments available for telepresence surgery

RESULTS

The surgeons who used the telepresence surgery system received no special training, and, after a short practice period on *ex vivo* tissues, were able to use the system successfully to operate on live animals. Tissue manipulation, dissection, incision, and suturing were all performed without observable errors. In cholecystectomies, cystic ducts and arteries were readily identified, isolated, and ligated. Gallbladders were dissected free from the liver without damage to either organ. Gastrotomy closures, performed in two layers, and inverting enterotomy closures appeared identical to procedures in which conventional, open surgical techniques were used.

Liver lacerations were closed with mattressed sutures or with advanced fibrin hemostatic bandages. Both methods controlled steady bleeding, without causing further tissue damage. Patency of vessels was maintained after arterial repairs, and no hemorrhage was noted from suture lines (Figure 2).

The times required for procedures performed with the telepresence surgery system were two to three times longer than those performed with conventional operative techniques. Increased times were required for tissue dissection, suturing, and knot tying, with no one component predominating in length. Prolonged use of the system resulted in only minimal decrease in task performance times.

DISCUSSION

The obvious uses of telepresence surgery are in extending the expertise of a surgeon to locations where that is not currently possible. On the battlefield, casualties die from exsanguinating hemorrhage. By using a mobile military vehicle equipped with a remote surgical unit and nonphysician medical assistant, a surgeon operating from a field hospital 30 to 70 miles away could perform life-saving, stabilizing procedures that would allow casualties to be safely evacuated for definitive care.[5] Basic procedures performed in trauma surgery could be successfully performed with the telepresence system.

The increased times required for task completion with the telepresence surgery system were consistent, and most likely resulted from the constraints imposed by having only four degrees of freedom in the manipulator arms, whose range of motion simulates a

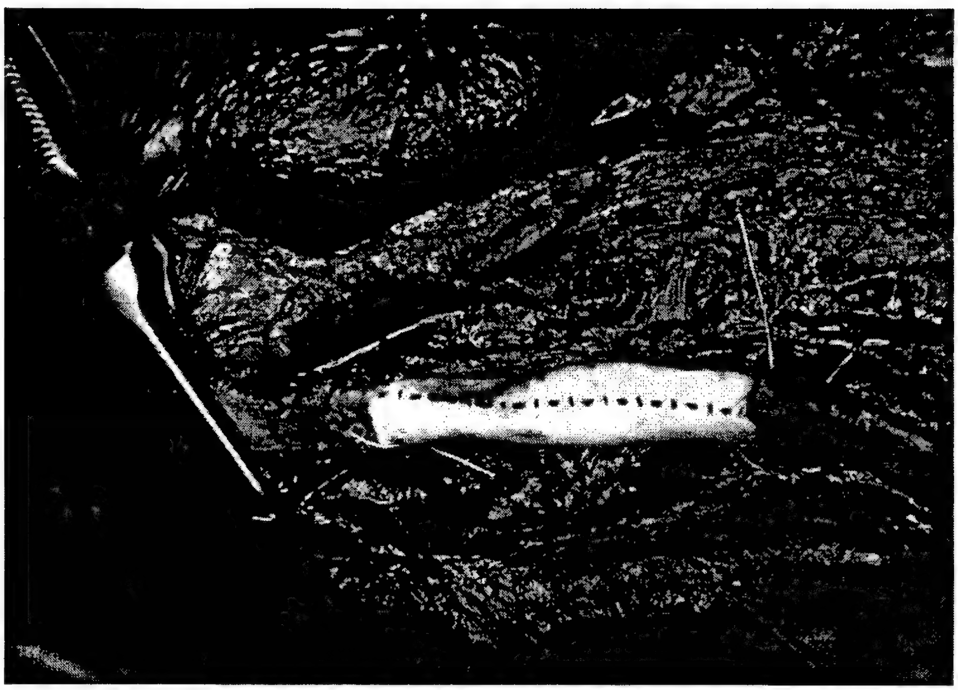


Figure 2. PTFE aortic interposition graft replacing excised segment of infrarenal aorta

human upper extremity with a nonmobile (fused) wrist. This limitation was most apparent to surgeons when dissecting or suturing tissues on an axis parallel to the remote surgical unit's orientation. Although the feasibility of telepresence surgery was apparent despite this limitation, improved wrist functions will be required for clinical acceptance. The next-generation system, now being assembled at SRI, will provide a full seven degrees of freedom in the manipulator arms. With this improvement, a surgeon will be able to operate freely about all axes of rotation.

Surgeons readily adapt to performing under adverse conditions. Laparoscopic surgery reduces the tactile feedback available to a surgeon, removes stereoscopic visual cues, and introduces an abnormal instrument fulcrum at the anterior abdominal wall. Yet in a short period of time, minimally invasive techniques have been adapted to the performance of many gastrointestinal procedures.[6] Similarly, surgeons can achieve good results under adverse lighting and exposure. Therefore, to accurately assess the performance of a telepresence surgery system, it is not enough to conduct time and motion studies in isolated *ex vivo* tasks on inanimate objects. Surgical procedures requiring the real-time assimilation of information and integration of component tasks will be the benchmarks for development of system specifications.

Mobile telepresence surgery will require wireless microwave links between the surgeon's console and the remote surgical unit.[7] Key performance issues related to data packaging and transmission must be addressed. Specifically, the image resolution needed for a surgeon to accurately perform surgery will determine the bandwidth requirements and the potential for image compression. In addition, the lag times in instrument response that are acceptable to a surgeon must be determined.

The role of telepresence surgery in the operating environment of the future remains to be established. On the basis of our experience with the first complete prototype system available, however, we conclude that telepresence technology clearly has the potential to revolutionize the practice of surgery.

ACKNOWLEDGMENTS

This work was supported by the National Institutes of Health, under Grant GM 44902, and by the Advanced Research Projects Agency (ARPA) under Contract N00014-94-C-0040, and Grant DAMD17-95-I-5019.

REFERENCES

1. P.S. Green, T.A. Piantanida, J.W. Hill, et al., 1992: "Telepresence dexterous procedures in a virtual operating field," (abstr.) *Am. Surgeon*, **57**:92.

2. P.S. Green, J.W. Hill, J.F. Jensen, and A. Shah, 1995: "Telepresence surgery," *IEEE Med. Biol.*, **14**:326-329.

3. J.W. Hill, P.S. Green, J.F. Jensen, and A. Shah, 1994: "Telepresence surgery demonstration system," *IEEE Conf. Robotics and Automation*, **3**:2302-2307.

4. J.C. Bowersox, A. Shah, J.F. Jensen, J.W. Hill, P.R. Cordts, and P.S. Green: "Applications of a telepresence surgery system in vascular surgery," *J. Vasc. Surg.* (in press).

5. R. Zajtchuk and G.R. Sullivan, 1995: "Battlefield trauma care: focus on advanced technology," *Milit. Med.*, **160**:1-7.

6. A. Cuschieri, 1992: "The spectrum of laparoscopic surgery," *World J. Surg.*, **16**:1089-1097.

7. P.S. Green, J.F. Jensen, J.W. Hill, and A. Shah: "Mobile telepresence surgery," *J. Image Guided Surg.* (in press)

Health Care in the Information Age
H. Sieburg, S. Weghorst, and K. Morgan (Eds.)
IOS Press and Ohmsha, 1996

Chapter 13

Advanced Telepresence Surgery System Development

Joel F. Jensen and John W. Hill

Medical Technology Laboratory, SRI International, 333 Ravenswood Avenue, Menlo Park, CA 94025

ABSTRACT

SRI International is currently developing a prototype remote telepresence surgery system, for the Advanced Research Projects Agency (ARPA), that will bring life-saving surgical care to wounded soldiers in the zone of combat. Remote surgery also has potentially important applications in civilian medicine. In addition, telepresence will find wide medical use in *local* surgery, in endoscopic, laparoscopic, and microsurgery applications. Key elements of the telepresence technology now being developed for ARPA, including the telepresence surgeon's workstation (TSW) and associated servo control systems, will have direct application to these areas of minimally invasive surgery. The TSW technology will also find use in surgical training, where it will provide an immersive visual and haptic interface for interaction with computer-based anatomical models. In this paper, we discuss our ongoing development of the MEDFAST telesurgery system, focusing on the TSW man-machine interface and its associated servo control electronics.

INTRODUCTION

SRI International is currently developing a prototype remote telepresence surgery system, for the Advanced Research Projects Agency (ARPA), that will bring life-saving surgical care to critically wounded soldiers in the combat zone (CZ). Using SRI's

telepresence technology, a surgeon located in a mobile army surgical hospital (MASH) unit or base hospital will carry out emergency surgical procedures on soldiers in an armored mobile surgical vehicle in the CZ. Dubbed the *Medical Emergency Forward Area Surgical Telepresence* (MEDFAST) system, this vehicle will contain a fully equipped telepresence operating theater, and a medic in the MEDFAST will assist the remote surgeon.

Remote telepresence surgery also has applications in civilian medicine, where it will enable specialists in regional medical centers to treat patients in outlying clinics. In addition, telepresence will most likely find wide medical use in *local* surgery—in endoscopic, laparoscopic, and microsurgery applications, and will play an important role in surgical training, providing an immersive visual and haptic interface to computer-based anatomical models.

In current practice, microsurgery involves delicate manipulation of small tissue structures viewed through a stereo microscope. While major reconstructive efforts such as reattachment of severed digits are routinely performed, these microsurgical procedures are often long and exhausting, with the surgeon spending many hours of concentrated work looking through microscope eyepieces, sitting in an awkward position [Franken et al., 1995]. In addition, human performance limitations preclude the extension of microsurgical techniques to new applications using higher magnification. The time to complete a task increases in proportion to the visual magnification required to complete it [Szabo, 1994]. Therefore, increases in magnification result in longer procedures, which increase patient risk and incur greater financial costs.

Similar limitations exist for laparoscopic surgery as currently practiced. It has largely replaced open surgery for relatively simple procedures such as cholecystectomy and hernia repair, and brings substantial benefits to the patient, including shorter hospital stay, faster recovery, and less cosmetic damage. However, with current instrumentation, laparoscopic procedures require more operating room time and are much more difficult for the surgeon than equivalent open procedures. As a result, relatively few surgeons will be able to progress from laparoscopic cholecystectomy to more complex procedures in the bowel and esophagus. The problem: laparoscopic surgery currently entails awkwardly maneuvering long instruments that are fulcrumed in the patient's abdominal wall (so that the motion of the tool tips is opposite to the motions of the surgeon's hands), while viewing the surgical field on a 2D video display located on a stand above the patient. This arrangement makes hand-eye coordination very difficult, and provides the surgeon with very little force feedback.

SRI's telepresence technology can overcome many of the limitations imposed by current minimally invasive surgery (MIS) instrumentation and methods. By enabling a great increase in the range and number of procedures that can be performed, telepresence will bring the benefits of MIS to many more patients.

In the case of microsurgery, telepresence systems will provide motion and visual scaling along with amplified force feedback that will allow surgeons to perform microsurgical procedures with the same speed, skill, and dexterity they achieve in full-scale open surgery. Similarly, for laparoscopic and other endoscopic procedures,

telepresence systems will provide an intuitive and effective interface for telepresence surgery that will greatly enhance surgeons' capabilities.

Key elements of the MEDFAST system we are now developing, including the telepresence surgeon's workstation (TSW) and associated servo electronics, will find direct use in these MIS telepresence systems and will play an important role in future MIS practice. In addition, the new TSW will be useful in surgical training, providing an excellent visual and haptic interface for interaction with computer-based anatomical models.

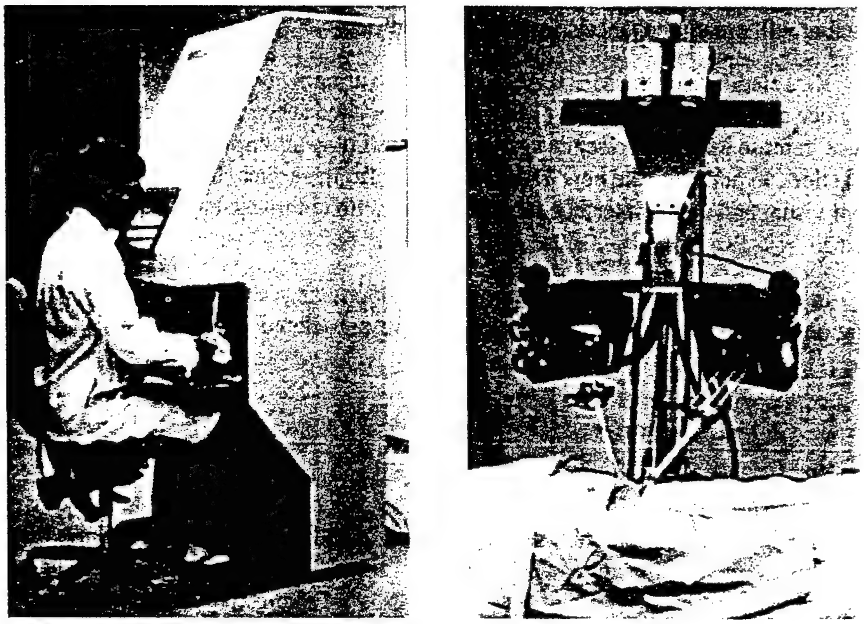
In this paper we discuss our ongoing development of the MEDFAST system, focusing on the TSW man-machine interface and its associated servo control electronics.

BACKGROUND

SRI International has previously developed and demonstrated a prototype telepresence surgery system [Green et al., 1995] that has been used to perform successful remote surgical procedures on animals. Other robotic and telerobotic systems have been developed for surgical applications [Burckhardt et al., 1995; Taylor et al., 1994], but only the SRI system provides the combination of responsive, force-reflecting telemanipulators and integrated visual feedback that allows surgeons to remotely perform the full spectrum of surgical maneuvers—for example, cutting, suturing, dissecting—with a high degree of dexterity and effectiveness comparable to their hands-on skills.

The SRI telepresence technology is an entirely new method of remote manipulation, with important potential applications in remote surgery and MIS. Surgeons who have worked with SRI's telepresence surgery demonstration system, with its fully integrated combination of three-dimensional (3D) video imaging, precise remote manipulation with handheld surgical instruments, and force feedback, agree that it is so compellingly realistic as to immediately dispel any sense of remote operation. Using the demonstration system, these surgeons have successfully performed three series of remote surgical procedures on pigs [Bowersox et al., 1996]. These first-ever remote surgeries included treatment of a variety of simulated abdominal and vascular injuries, including cholecystectomy, nephrectomy, repair of gastrotomy and enterotomy, and repair of femoral artery, liver, and bladder lacerations.

Shown in Figure 1, the demonstration system consists of two modules: a work-site module, where the actual object manipulation takes place, and an operator module that contains a strikingly realistic, 3D, video reproduction of the actual work space (not a computer model). This demonstration system incorporates many advanced technologies, including a highly responsive, force-reflecting master/slave manipulator with 4 degrees of freedom (DOF), stereoscopic video, and stereophonic sound. In effect, the operator grasps surgical instruments, reaches into what appears to be the actual workspace, and carries out complex tasks with quick, sure motions. Operating surgeons feel as though they are performing tasks right before their own eyes. The 3D image is created by a stereographic video system, viewed with a mirror. The surgeon looks downward, "through" the mirror, to see the surgical site below it, just where he or she is reaching



(a) The telepresence surgeon's workstation of the demonstration system provides two hand-control masters with surgical instrument handles, a stereographic view of the surgical field, and a microphone and speakers for communicating with the assistant at the remote site.

(b) The demonstration system remote surgery unit comprises two slave manipulators with interchangeable surgical instruments, a pair of stereographic video cameras, and stereo microphones.

Figure 1. Demonstration telepresence surgery system

with the hand controls. The control is a surgical-instrument handle mounted on a light, well-balanced, force-reflecting servo manipulator—the *master*. An identical *slave* servo manipulator at the operating table controls the actual surgical instrument—scalpel, forceps, and so forth—the tip of which is seen in the image, as if it were actually attached to the handle. When the tip touches the tissue, the resistance is felt from the handle. The overall effect is very compelling. With support from the National Institutes of Health, ARPA, and other sources, SRI has continued the development of this technology for remote surgery as well as laparoscopic and microsurgery applications.

THE ADVANCED SURGERY SYSTEM

System Block Diagram

- A simplified block diagram of the advanced system is shown in Figure 2. We have established specifications for the master and slave telemanipulators and the stereo video display. These specifications, which form the basis for the TSW design, are summarized below.

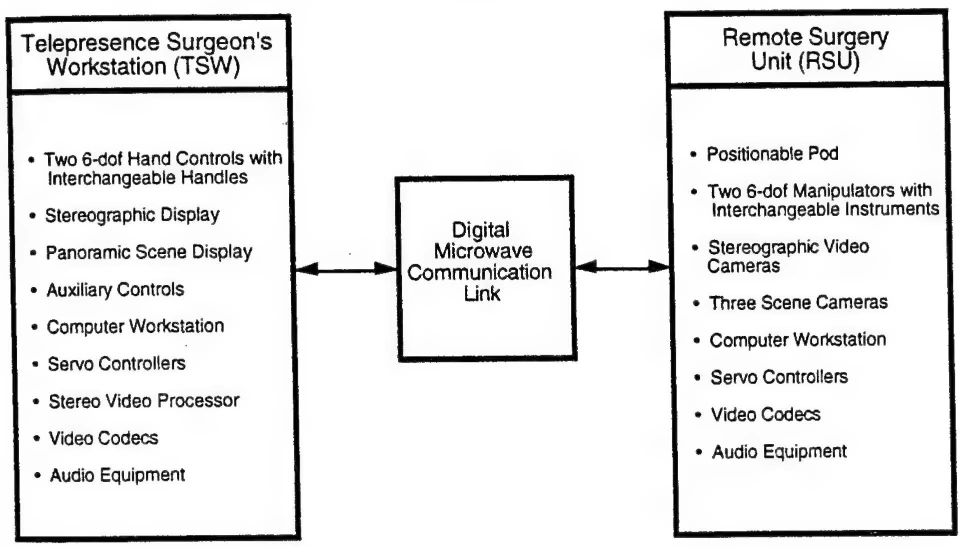


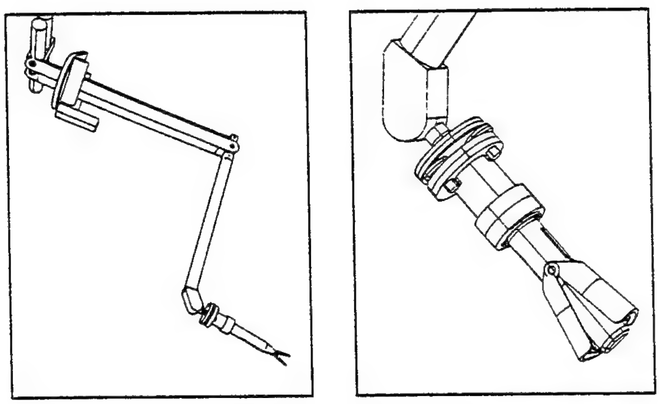
Figure 2. MEDFAST system block diagram. The MEDFAST system consists of the telepresence surgeon's workstation (TSW), the communication link, the remote surgery unit (RSU), and electronics modules associated with the TSW and RSU.

- Control handles for master manipulators, interchangeable for surgeon's use with either right or left hand
  - Hemostat handle
  - Forceps (pickup) handle
- Stereo vision system
  - Display resolution: 640 x 480 pixels, minimum
  - Camera resolution: 700 horizontal by 494 vertical lines
  - Stereo display type: 120 Hz full-frame with active or passive glasses

The New TSW

Based on the above specifications, we are developing a new TSW with two 6-DOF (plus grip) hand controls, enhanced displays, auxiliary controls, and all-new, ruggedized electronics. Using wood and metal mock-ups, we have had consulting surgeons perform simulated procedures, including suturing organ models, to evaluate the range of motions required for surgical procedures and guide our designs as they evolve. The surgeons are experienced in trauma, general, and vascular surgery, as well as other surgical specialties.

Master Manipulator Design: The proposed manipulator design is shown in Figure 3.



(a) Overview of manipulator

(b) Detail of master with pickup handle

Figure 3. Design of surgical manipulators

TSW Console Human Factors: The new surgeon's console has been designed to accommodate surgeons with a wide range of physical statures. The design will comfortably seat men and women ranging from the 5th to the 95th percentile in height, and will enable effective telepresence for all of them. Figure 4, based on data from Woodson and Conover [1964], illustrates the latitude of adjustment necessary. Our plan is to have the surgeon sit on a chair of adjustable height, which will bring his or her eyes to the proper location to view the display. A foot rest with foot controls will be brought up to match a comfortable foot height, and (if necessary) the master arms can be adjusted up or down to a comfortable position.

To accommodate the 6-DOF manipulators, the new surgeon's console will need to provide a much larger workspace than is afforded by the current console. Accordingly, the new console is designed to allow unimpeded motion of the control handles throughout a range of at least 1 cubic foot directly in front of the surgeon, to allow rapid and effective surgical treatment of trauma. The conceptual design is shown in Figures 5a, 5b, and 5c. For finer, more controlled procedures, such as suturing and micro dissecting, the console will include positionable forearm rests for stabilization.

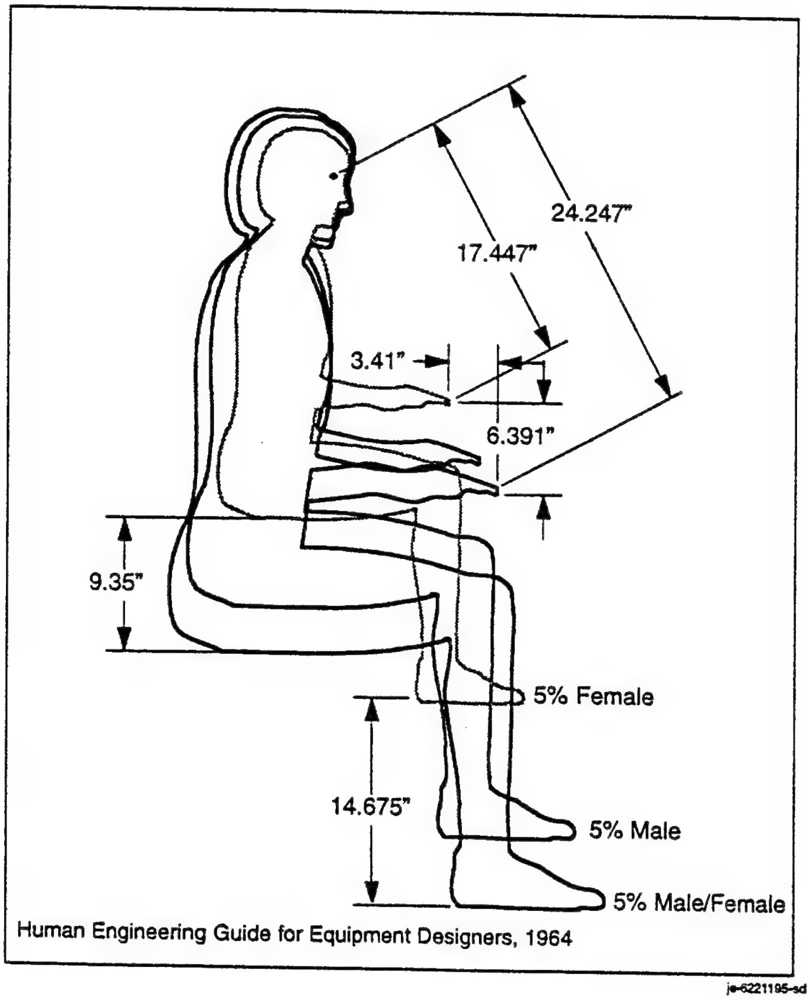
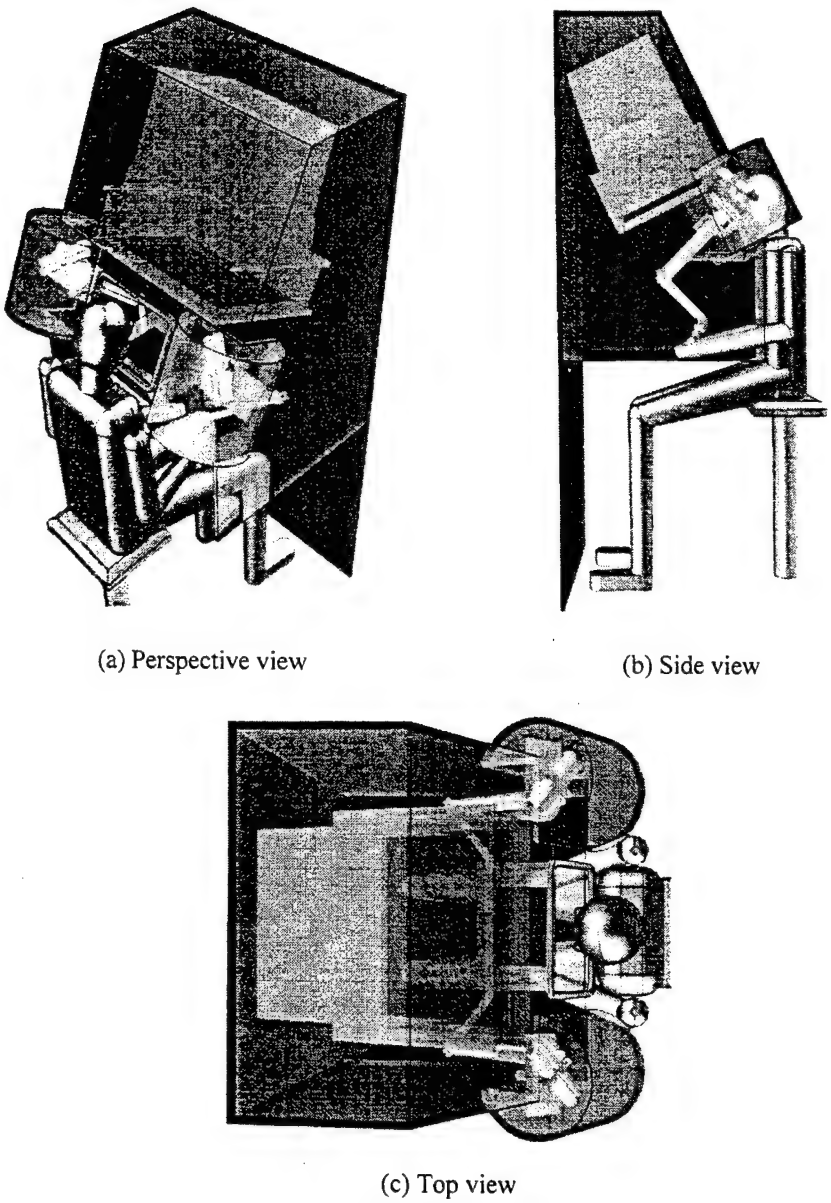


Figure 4. Variation in human dimensions



(a) Perspective view

(b) Side view

(c) Top view

Figure 5. Design of telepresence surgeon's workstation

Both the stereographic display and heads-up display are also included in the surgeon's workstation. The stereo display is viewed through a mirror as in our initial telepresence demonstration system. The heads-up display (not shown in Figure 5) will be at the back of the TSW console. Additional items not shown include foot controls, audio microphone, and stereo speakers.

Servo Controller

New servo electronics and algorithms have been developed to control the 6-DOF master and slave manipulators. To enable enhanced tactile feedback, enhanced dynamic response, and greater manipulator output force, we have developed and tested new control algorithms that employ a combination of force and position feedback. The algorithms have been tested using simulation and actual operation on a single-axis test stand.

Simulation: We have developed a model of our DSP-based controller and a motor-driven test axis using Matlab and SIMULINK (products of Math Works, Inc.) to aid in developing and testing different bilateral servo algorithms. We constructed a detailed analytical and numerical model of our control hardware and the dynamics of the servo control test stand so as to better understand the control issues and to speed and facilitate alternative control designs. The model includes discrete sampling effects and real-time computation delay effects.

Servo Test Stand: We have built a single-axis servo test stand to verify the simulation results. The test stand consists of two motor-driven axes with gearing and inertia similar to the elbow axis of the new manipulators. Each axis has a tachometer and potentiometer for determining step and frequency response. In addition, an external drive motor on one axis produces sinusoidal input (simulating operator hand motion) at different frequencies for determining transfer functions. A force sensor on the tip of each arm, sensitive to ±2 lb, is interfaced to the analog inputs of our servo controller.

Evaluation of Control Laws: We have evaluated the following known control laws for bilateral, force-reflecting control of teleoperated manipulators.

- **Position/position control**: First introduced over thirty years ago [Burnett, 1957], position/position control used bilateral position tracking to introduce some force reflection into a teleoperated manipulator.
- **Power steering and position/position control**: Local power steering can be introduced into the position/position control scheme by feeding back a force measurement to the local controller.
- **Position/position control and cross-coupled force reflection**: Power steering is made symmetric by passing force measurements between master and slave.
- **Position forward/force back**: This is an asymmetric control objective that has the slave manipulator follow the master manipulator's position only, while the master manipulator follows the slave's force measurement only [Flateau, 1969]. Additional damping is provided by some velocity feedback. This approach can an be used with a single (slave) force sensor.
- **Ideal kinesthetic coupling**: A physically derived control law using acceleration feed forward and cross-coupled force measurements provides "ideal kinesthetic coupling" [Yokokohji and Yoshikawa, 1994].

We are currently evaluating each of the control laws listed in Table 1 with computer models and the single-axis servo test stand.

Table 1

KINESTHETIC COUPLING CONTROL LAWS

	Performance	Passive	Optimality and Tuning
Bilateral position tracking (BPT)	Tracks position, force tracking contaminated by manipulator inertia	Yes	No automatic tuning, suboptimal performance
Power steering with BPT	Reduced inertia compared to BPT alone, loss of contact stiffness	No	No automatic tuning, suboptimal performance
Bilateral force amplification with BPT	Good stiffness and low inertia	No	No automatic tuning, suboptimal performance
Position forward/ force back	Good stiffness and low inertia, can be used with single force sensor	No	No automatic tuning, suboptimal performance
Ideal kinesthetic coupling	Good stiffness and low inertia	Yes	Model-based tuning, suboptimal performance (acceleration filtering)

New Control Electronics: New control electronics have been designed and built to accommodate both force- and position-feedback signals.

COMMENTS AND CONCLUSIONS

As part of SRI's ongoing project to develop a MEDFAST telesurgery system for ARPA, we are developing an advanced TSW design that will enable highly effective telepresence for remote surgery as well as MIS applications, and will also serve as an excellent immersive interface for surgical training using computer-based anatomical models. The TSW will include 6-DOF (plus grip) force-reflecting master manipulators, high-resolution 3D video, heads-up peripheral video displays, foot switches, and other I/O devices. The new console will allow unimpeded motion of the master control handles throughout a range of at least 1 cubic foot directly in front of the surgeon, enabling rapid and effective surgical treatment

ACKNOWLEDGMENTS

This work was supported in part by SRI International and in part by the National Institutes of Health, under Grant No. GM 44902, and by the Advanced Research Projects

Agency (ARPA) under Contract N00014-94-C-0040, P.O. number 32858 from Assurance Technology Corp. (Government Contract N00014-93-D-2022), and Grant DAMD17-95-I-5019. The views represented in this article are those of the authors and do not reflect the official policy of the Department of Defense or the U.S. Government (approved for public release, distribution unlimited).

REFERENCES

Bowersox, J.C., A.S. Shah, J.F. Jensen, J.W. Hill, and P.S. Green, "Vascular Applications of Telepresence Surgery: Initial Feasibility in Swine," *J. Vasc. Surgery*, in press (1996).

Burckhardt, C.W., P. Flury, and D. Glauser, "Stereotactic Brain Surgery," *IEEE EMBS Magazine*, Vol. 14, No. 3, pp. 314–316 (May/June 1995).

Burnett, J.R., "Force-Reflecting Servos Add 'Feel' to Remote Controls," *Control Engineering*, Vol. 4, No. 7, pp. 1269–1274 (1957).

Flatau, C.R., "Compact Servo Master-Salve Manipulator with Optimized Communication Links," *Proc. 17th Conf. Remote Systems Technology*, pp. 154–164 (November 1969).

Franken, R., S.C. Gupa, S.R. Rod, S.V. Thomas, J.H. Barker, M. Kon, and J.C. Banis: "Microsurgery without a Microscope: Development of a Three-Dimensional On-screen Microsurgery System (TOMS)," *J. Medicine and Virtual Reality*, Vol. 1, No. 1, pp. 26–32 (1995).

Green, P.S., J.W. Hill, J.F. Jensen, and A. Shah: "Telepresence Surgery," *IEEE Eng. Medicine and Biology*, pp. 324–329 (May/June 1995).

Szabo, Z.: Personal communication, Director, MOET, San Francisco (1994).

Taylor, R.H., et al., "An Image-Directed Robotic System for Precise Orthopaedic Surgery," *IEEE Trans. Robotics and Automation*, Vol. 10, No. 3, pp. 261–265 (1994).

Woodson, W., and D. Conover, *Human Engineering Guide for Equipment Designers*, 2nd Edition, University of California Press (1964).

Yokokohji, Y., and T. Yoshikawa, "Bilateral Control of Master-Slave Manipulators for Ideal Kinesthetic Coupling-Formulation and Experiment," *IEEE Trans. Robotics and Automation,* Vol. 10, No. 5, pp. 605–620 (1994).

Telepresence Technology in Medicine: Principles and Applications

JOHN W. HILL, MEMBER, IEEE, AND JOEL F. JENSEN

Invited Paper

Telepresence systems can improve surgeons' performance in minimally invasive surgery (MIS) and microsurgery and also enable them to operate on patients remotely over great distances. In MIS, telepresence technology allows surgeons to experience surgery as if their hands and eyes were effectively inside the patient's closed abdomen, enabling them to work with improved skill and dexterity. In microsurgery, the technology can scale down the surgeons' motions, forces, and field of view, allowing them to skillfully operate on microscopic anatomy with relative ease. Our systems also enable surgeons to treat patients remotely in inaccessible or hazardous locations with great effectiveness, allowing them to operate as if they were present at the remote site. The means for conveying human presence in such systems is through force-reflecting manipulators with digital servo controllers, stereo viewing systems, and communication links. Depending on the application, the surgeon at the telepresence workstation may be across the room from the patient or across the state, connected by a microwave link or communication network.

Keywords— *Dexterous manipulators, micromanipulator, minimally invasive surgery, surgery, surgical simulation, telepresence, telerobotics, virtual reality.*

I. Introduction and Background

A. Teleoperation

Teleoperation systems have made it possible for man to reprocess plutonium, service satellites in space, and perform deep-sea salvage operations from a safe control room by using remote manipulators and communication links. These systems are typically operated by teams of engineers acting on data from walls full of computer displays. Remote work with these systems is frustratingly awkward compared to on-site, hands-on operation and is typically 10–20 times slower.

Manuscript received July 16, 1997; revised October 20, 1997. This work was supported in part by SRI International; the National Institutes of Health under Grant GM 44902; the Defense Advanced Research Projects Agency under DARPA Contract N00014-94-C-0040, P.O. 32858, Assurance Technology Corp. (Government Contract N00014-93-D-2022); and the Advanced Biomedical Technology Program under Grant DAMD17-95-I-5019.

The authors are with SRI International, Menlo Park, CA 94025 USA (e-mail: john_hill@qm.sri.com; jjensen@unix.sri.com).

Publisher Item Identifier S 0018-9219(98)01731-9.

Major contributions to the design of mechanisms and control for telerobotic manipulators originated in the nuclear industry. Examples of this work include the Argonne Mark-E4A [1] and the Brookhaven Arm [2]. This early work led to more refined bilateral force-reflecting manipulators [3], [4].

B. Telepresence

Telepresence is an enhanced form of teleoperation that employs an immersive and transparent user interface, permitting the user to work with high effectiveness in inaccessible or remote environments. In telepresence surgery, the surgeon works at a telepresence surgeon's workstation (TSW), using familiar instruments and intuitively responding to the stereoscopic view, proprioceptive and haptic cues, and sounds that are provided as feedback from the actual surgical site. With telepresence, the user can remotely perform complex tasks without the need of specialized training.

Using modern telemanipulator, control, and imaging capabilities, we have developed systems that enable the full spectrum of surgical tasks—such as cutting, suturing, and dissecting—normally performed by surgeons. Systems with the required dexterity, speed, and delicate force feedback have not been previously developed, nor has a human interface methodology for making their use natural and effective.

The application of telepresence principles to surgery has several potential benefits:

- in minimally invasive surgery (MIS), restoring the hand–eye coordination that is lost when surgeons use conventional instruments, thus speeding up a slow and fatiguing manual process and bringing the benefits of MIS techniques to more patients;
- in microsurgery, scaling small motions and forces to the optimal range of human perception, thereby enabling improved performance and new microsurgical procedures;
- bringing lifesaving surgical care to isolated patients in rural areas, aboard ship, or on the battlefield;

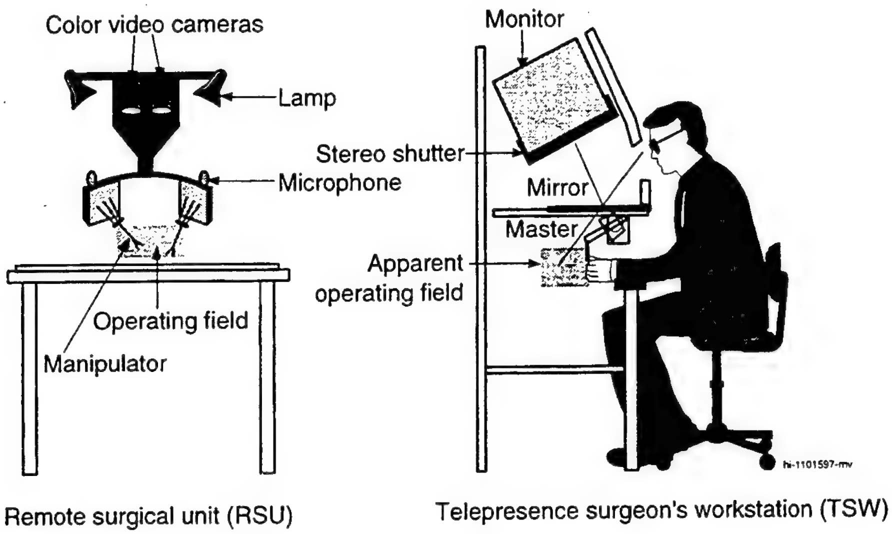


Fig. 1. SRI telepresence surgery principle.

- in all surgery, opening surgical procedures to the benefits of telemedicine;
- in training of medical students, interacting with computer simulations through a natural, immersive interface;
- in preparation for surgery, allowing the surgeon to practice surgery on a "virtual patient" computer model created from patient-specific medical image data.

C. Background

Robots have begun to find applications in surgery in recent years [5], [6]. For example, placement of probes in the brain has been demonstrated using a stereotactic robot positioner [7]. Typically, the robot inserts a needle along its axis deep into a tumor. The "Robodoc" orthopedic surgery system, developed at IBM and Integrated Surgical Systems [8], produces a precise cavity in the femur for hip replacement. Transurethral resection of the prostate has also been performed robotically [9].

In contrast to robot automation, earlier researchers have envisioned the potential advantages of telemanipulation in surgery. These advantages include a concept for a teleoperator surgery system in which the surgeon could see and feel what he is operating on [10]. Examples of prototype systems are a handheld master with a pencil-like tool [11], a finger-sized manipulator (four links) proposed for corneal transplant surgery [12], and a three-axis manipulator for cutting [13].

D. SRI Telepresence Principle (Immersive Interface)

Alexander [14] described a concept for remote surgery in 1973 and made a conceptual sketch of a remotely operated system for MIS. The sketch shows a system with master hand controllers under a mirror to align hand and eye axes and make manipulation more intuitive. The first implementation of a prototype telepresence surgery system integrating remote vision, sound, hand motion, and force feedback was developed by a team at SRI International led by P. S. Green [15].

The SRI telepresence principle or "Green Telepresence System" is diagrammed in Fig. 1. It consists of two modules: the TSW and the remote surgical unit (RSU). The TSW contains a color monitor for stereographic viewing (the operator wears passive polarized glasses or active shutter glasses), reflected in a mirror to create a "virtual workspace." Beneath the mirror are mounted stereo speakers and (one) hand-operated master manipulator, which is outfitted with a surgical instrument handle.

The RSU, shown on the left side of Fig. 1, captures stereo images with a pair of color video cameras converged at about 8°, the same interocular viewing disparity that we experience with a visual field 500 mm in front of us. Also included are a force-reflecting slave manipulator with surgical instrument jaws for grasping and a pair of microphones for stereo sound pickup.

The master and slave manipulators are placed in juxtaposition to the camera and to the display, respectively, so as to be geometrically identical. Our purpose is effectively to transport the operator to a remote site with adequate fidelity that he feels that he is actually there. This results in natural and instinctive control motions by the operator, who can make use of the innate and instinctive senses and reactions that have been practiced and perfected since birth.

The telepresence surgeon grasps surgical instrument handles, looks down into a three-dimensional (3-D) surgical field, reaches into the field with the instruments, and operates. He sees the tips of the instruments move with his hands as they manipulate the tissues and feels the tissues resist. To the surgeon, this looks and feels like the conventional open surgery on which he has already trained and practiced. At the slave site (i.e., the patient location), the technique may be MIS, microsurgery, or open surgery, and the patient could be in the same room or in the next state: it makes no difference. Telepresence provides such a compelling sense of reality that the surgeon is drawn immediately into the work, with no sensation of remote control. Hand motions are quick and precise.

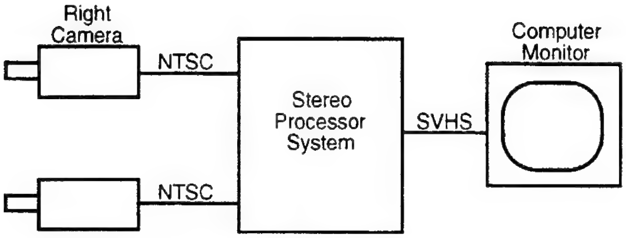


Fig. 2. Stereo display system. Video images from the cameras are acquired and buffered at 30 frames/s and alternately displayed at 120 Hz.

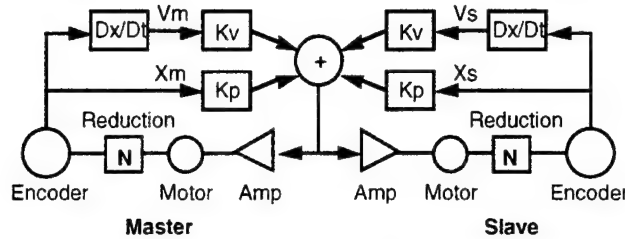


Fig. 3. Bilateral control system. The position and velocity of each joint as derived from the joint encoders are multiplied by the position and velocity gains, Kp and Kv, and input to both motors to provide joint torque.

II. Telepresence Technology Principles

A. Remote Stereoscopic Imaging

Ideally, visual information provided to the surgeon should take full advantage of the resolution capability of humans. Accomplishing this with a 225 × 300-mm (17-in) video monitor placed 500 mm in front of the eye would require a horizontal resolution of 2000–4000 lines [16].

Emerging high-definition television (HDTV) systems can now provide up to 2000 lines of horizontal resolution, but HDTV camera components are not yet available in configurations suitable for telesurgery applications. For our telepresence systems, we have selected commercial equipment with the highest resolution currently available.

The stereo imaging subsystem shown in Fig. 2 is representative of those used in our telepresence viewing systems. Two video cameras capture the stereoscopic image frames. Dual, digital frame buffers store the frame pairs at 30 frames/s and alternately provide left- and right-frame images to the operator's display at 120 Hz. Two shuttering methods are commonly used to ensure that each eye sees only the proper (left or right) image:

- a synchronously switched polarizing filter in close contact with the monitor combined with passive, polarized glasses worn by the observer;
- synchronously switched active shutter glasses worn by the observer.

Both methods pass alternate frames to the left and right eye, respectively. The 60-Hz presentation at each eye provides flicker-free viewing.

Alternative configurations use separate display monitors for each eye or head-mounted displays, eliminating the need for a synchronous shutter.

Principal design factors in stereo viewing systems are spatial resolution, field of view, contrast ratio, convergence, depth of field, and (in single-display systems) extinction ratio for the stereo shutter. Head-aimed systems introduce slew rate limitations for pitch and yaw as well as convergence. Distortions in viewing geometry, which lead to misperceptions, can be introduced at both the camera and display [17]. Supplementary visual information as a heads-up display, patient monitor, or image overlays can be introduced to augment the visual information. Well-designed viewing systems permit the surgeon to position tools accurately at the desired location and create a sense of "immersion."

B. Force-Reflecting Master–Slave Manipulators

For efficient performance in surgery, the handles at the master manipulators should act and feel like familiar surgical tools. In this way, prior surgical training is rapidly transferred to the telerobotic system. The master manipulator should impose a low mass load (25–35 g) on the operator's hand and have an adequate range of motion in six degrees of freedom (dof) [18]. It should have unnoticeable friction and damping, move freely at up to 1 m/s, and have a bandwidth of at least 10 Hz [19], [20] to avoid tiring the operator. Higher bandwidth is desirable for conveying the feel of vibration and hard contact.

Master–slave manipulator design differs from industrial robot design in that the mechanism must have low inertia. To accomplish this, the actuators must be located appropriately so that their mass does not cause undesirable loading. Friction is minimized by using few stages of gearing, low-friction/low-inertia actuators, and low-friction bearings throughout.

Force feedback is provided on all axes of the manipulator, including the gripper closing force. Forces and torques generated as the tool touches objects in the course of its work are reproduced at the operator's hand by the control system. Soft objects must feel soft, and hard ones hard. The force feedback from the actions of probing, dissecting, cutting, and suturing should be clear and natural to maximize surgical performance.

Principal design factors in manipulators are degrees of freedom and working volume. Other design specifications such as accuracy, backlash, friction, inertia, and bandwidth vary with position in working volume.

C. Control Systems

Bilateral control of manipulators encompasses research in appropriate control objectives, in algorithmic implementations, and in stability and robustness of controllers. Bilateral control objectives and implementations have taken various forms. A well-known bilateral control objective designed to achieve some force reflection is that of bilateral position tracking [21], as shown in Fig. 3. This technique is easily implemented and can be designed to be robust, but the user is burdened with the total inertia of both the master and slave on his hand.

Another common goal for bilateral control of manipulators is ideal (or transparent) coupling, where the objective is

to provide perfect position tracking between the master- and slave-end effectors while providing perfect reflection of the force at the slave-end effector to the master-end effector. Several control algorithms have been developed to approximate this ideal coupling. An early algorithm designed to achieve ideal coupling is the position-forward/force-back control scheme [2], where the slave manipulator is controlled to track the master's position while the master manipulator is controlled to track the slave's force. A modification to position tracking that includes bidirectional force measurements [22] was difficult to tune to ensure stability. Introducing planned compliance into the controller allowed for higher force reflection gains while retaining stability [23]. More recently, a physically motivated control algorithm was developed for realizing ideal kinesthetic coupling in a single-degree-of-freedom system based on position, velocity, acceleration, and force measurements [24].

A generalization of the control objective is that of mechanical impedance modification. Here, the controller is designed to modify the impedance of the environment as perceived by the operator [25]–[28]. Mechanical impedance modification is at the heart of bilateral control systems that act as "extenders" to increase human strength [29] and micromanipulators that scale down motion and scale up force [30].

Stability robustness of bilateral controllers when coupled to the operator and to varying environments is of critical importance [31], [32]. The requirement for stability of the closed-loop control system when coupled to passive, but otherwise arbitrary, loads and when power scaling is not required is known to be a passivity constraint on the control system [33]–[35]. When the bilateral controller is intended to scale power, the condition for robustness when the manipulator is coupled to an arbitrary, passive environment has been derived in terms of structured singular values of a scattering representation of the system [36].

Principal design factors in control systems are bandwidth/response time, controller order, update rate, and hardware implementation. Desirable bonuses are reductions of parasitic mass, friction, and damping forces felt by a human hand on the tool through the incorporation of force sensors. Using the ideal kinesthetic coupling algorithm [25], we have demonstrated a 50% reduction in hand-tool mass.

D. Aural Feedback System

Stereo sound feedback can enhance immersion and performance in remote tasks by allowing the surgeon to 1) assess his actions via the sounds they create, 2) take advantage of audible spatial location cues, and 3) talk to a remote assistant or a team in the procedures as if he were actually there.

Our remote open-surgery RSU's incorporate two microphones positioned above and to the sides of the work site itself. Two speakers are located in the TSW just above and to the sides of the hand-controller region—the apparent work site. Alternatively, a pair of earphones can be used. Either arrangement provides stereophonic sounds that seem to emanate from the work site and that are generally associated with the side of the work site from which they originated. The distance between the left and right microphone elements is approximately the same as the distance between the speakers that reproduce the sound. Design issues are the sensitivity, frequency response, and location of the microphones and speakers.

E. Telecommunication Links for Telepresence

The communication link between the TSW and RSU can take a variety of forms, depending on system requirements, ranging from copper cabling to microwave radio links and optical fiber connections. In each case, however, it is important to consider the separate requirements for the servo and video communication channels. The servo data are inherently digital and require a bandwidth of only about 300 kb/s but must have a latency of less than about 5 ms. (Time delays produce a viscous drag phenomenon in the servo system, which can be compensated for by using phase lead up to about 5 ms.)

Our camera outputs are currently analog, so the video channel can be analog or digital, and it can also tolerate greater latency (up to about 50 ms) before annoying delays become noticeable in updating the stereo image. To implement a fully digital communication link, we transmit the stereo video data by using conventional video codecs, which require one DS3 channel (45 Mb/s) for each video stream. As a result of our latency requirement, Motion Pictures Experts Group and other multiframe, high-compression schemes are not acceptable in the video communication channel. For local operation within the same hospital facility, analog video transmission over coaxial cabling may be an appropriate option. Digital video transmission is clearly required for transmission over wider networks.

Design parameters of the communication link are time delay, image distortion (through compression algorithms), and signal bandwidth for manipulator position and force signals.

F. Evaluation of Human Factors

Pioneering human performance work was conducted by Fitts [37], who showed that the time for manual positioning tasks is proportional to the logarithm of the ratio of the distance moved divided by the target width. He called this the task difficulty and measured it in bits. As target width decreases, task time increases, and the slope of this line gives the time constant of the exponentially decreasing hand–eye settling error. Fitts' law has been shown to apply to tasks with telemanipulators having two to six dof [38] and to force-reflecting telemanipulators by breaking Fitts' positioning task into an open-loop move and a vision/feel guided subtask [39], [40]. Complex telemanipulator tasks can be further broken down into elemental subtasks (e.g., move, turn, position, grip, fit) to compare force, vision, or other experimental conditions better [41]. This permits distinguishing open-loop tasks (move and turn elements), which do not depend upon force sensing, from closed-loop

tasks (position and fit elements), which depend on force and 3-D vision for completion. Depth-matching accuracy was measured (the Verhoff test) to compare 3-D displays with different interocular viewing distances [42]. Sheridan [43] summarizes contributions to manual performance measurement with different hand controls, tasks, control systems, viewing conditions, and time delays.

III. Current Application Areas

A. Telepresence Minimally Invasive Surgery System

1) Background: In recent years, MIS has largely replaced conventional open surgical techniques for removal of the gallbladder and the appendix and for other relatively simple abdominal procedures. MIS methods are slow to be adapted to more complex procedures, however, because current laparoscopic instruments are very awkward and cumbersome to use compared to those of open surgery.

A primary limitation is that the instruments are operated through an incision in the abdominal wall, which serves as a fulcrum, with the surgeon's hand on the opposite side of the fulcrum, away from the surgical site. Moreover, the video axis is not aligned with the hand axis, and the surgeon watches the instrument tips on a video screen across the operating room table, an arrangement that makes hand–eye coordination very difficult and engenders a feeling of disconnectedness. Consequently, every motion is deliberate rather than intuitive, and relatively simple maneuvers, such as suturing, are time consuming and frustrating.

Telepresence technology has the potential to overcome these limitations, enabling the expanded application of MIS to a wider range of more complex procedures and thus bringing the benefits of MIS to many more patients.

2) Work at Other Laboratories: Positioning the endoscope during laparoscopy requires an additional assistant during surgical procedures. To replace this function as well as to provide better control for the surgeon, several robotic scope positioners have been developed [44]–[47]. Control variations include speech recognition, head motion, and hand and foot switches.

An MIS manipulator system with remote-center manipulators has been demonstrated in Germany [48]. This approach includes force-reflecting manipulators, but the video display system does not maintain a natural hand–eye axis.

3) Work at SRI: At SRI, we have developed a prototype telepresence (T)MIS system designed to overcome the loss of hand–eye coordination and touch sensitivity that occurs with conventional MIS technology. In designing the prototype, we paid careful attention to the human factors involved in surgery and to the special demands of MIS.

The TSW shown in Fig. 4 employs a mirror to create a "virtual workspace" beneath the hand-operated master controllers.

The TSW has the following characteristics:

- *master manipulators:* each with a polar coordinate system with four dof (roll, pitch, yaw, and extension) with tool activation; workspace 200 mm high and wide by 100 mm in extension; continuous force of 7 N; friction approximately 0.3 N;
- *handgrips:* loop handles like those found on surgical forceps;
- *visual display:* 17-in Tektronix color stereo display (120 Hz) with integrated synchronous shutter and polarized glasses;
- *audio system:* stereo speakers providing aural feedback from the remote work site.

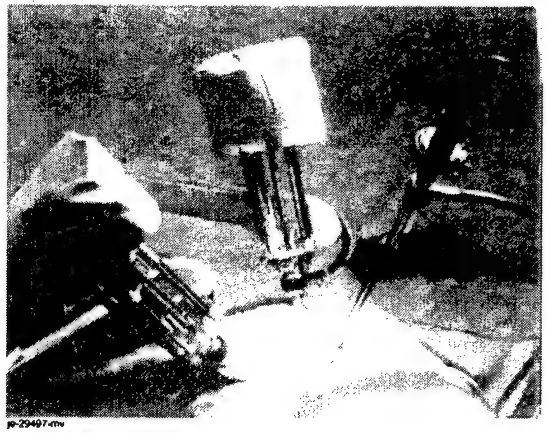
Fig. 4. Telepresence surgeon workstation for the MIS, microsurgery, and open-surgery systems.

The RSU of the TMIS system (Fig. 5) employs novel force-reflecting slave manipulators that maintain a remote center of rotation aligned with the tool entry point (i.e., the surgical incision) in the patient's abdominal wall.

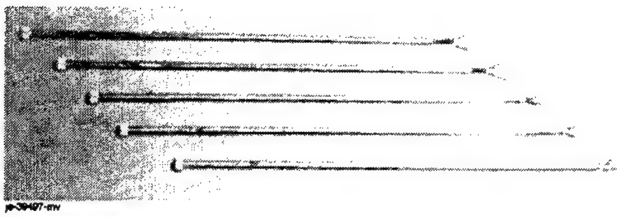
The RSU and TSW each incorporates a pair of manipulators, each with the same four dof (plus tool actuation) used in conventional MIS instruments. With telepresence, the surgeon's hand is effectively on the correct side of the fulcrum, so the tool tip precisely follows the surgeon's hand motion in a totally intuitive manner. The bilateral control system provides for magnified motion and sensitive force reflection. The low-inertia electromechanical design provides a high-bandwidth, low-drag system with surprising realism. System operation is intuitive and natural, no operator training is required, and remote tasks can be performed with a high degree of dexterity and skill.

The characteristics of the TMIS RSU are as follows:

- *slave manipulators:* each with a polar coordinate system with four dof (roll, pitch, yaw, and extension) plus tool actuation; workspace 250 mm in pitch and yaw, 150 mm in extension; continuous force of 7 N;
- *tools:* interchangeable needle holders, forceps, graspers, scissors (Fig. 5) to enable a range of MIS procedures;



(a)



(b)

Fig. 5. (a) Telepresence minimally invasive surgery system and remote surgical unit. (b) Set of replaceable tools.

- *control system:* bilateral position–position on rotation and extension axes, combined bilateral position and force back (active force sensing) on pitch and yaw; motion and force scaling;
- *imaging:* wolf stereo endoscope with xenon arc source, magnification variable from 5× to 30×.

Preliminary animal experiments and *in vitro* studies have been completed using the prototype TMIS system. The animal experiments were carried out using a porcine model, and cholecystectomies and other abdominal procedures were successfully performed with the system, with no aborted attempts or complications. Participating surgeons confirmed that—even with the four-dof prototype TMIS system—the procedures had a more "intuitive feel" than with conventional MIS instruments.

To more objectively evaluate the performance of the TMIS prototype, we have carried out a set of controlled *in vitro* experiments in which surgical residents performed a series of anastomosis and knot-tying tasks by using both the TMIS system and conventional MIS tools, in randomized order [49]. In both the anastomosis task (suturing together two pieces of synthetic blood vessel) and the knot-tying task, performance with the TMIS system was approximately 30% faster than with conventional MIS instruments. In addition, the leakage rate from the completed anastomoses was about 25% less with the TMIS system.

B. Telepresence Microsurgery System

1) Background: In current practice, microsurgery involves dexterous manipulations on small tissues viewed through a stereo microscope. Surgeons hold special grasping and cutting instruments in a pencil-like grip, with their palms supported, to optimize fine motor control and minimize hand tremor and fatigue. One instrument generally holds or applies tension while the other cuts or applies a needle.

Microsurgical tasks and skills used in surgical procedures across numerous specialties include ophthalmology, otology, digit-reattachment surgery, microvascular surgery, urology, obstetrics and gynecology, neurosurgery, and minimally invasive surgery [50], [51]. The tasks and skills required in all these specialties—specifically micropositioning, making incisions, microdissection, and suturing small vessels—are common, indicating the wide applicability of a microtelemanipulation system developed for this purpose.

Human limitations include:

1) procedures that are inherently physically exhausting, mainly due to the long hours of concentrated work in looking through microscope eyepieces, often with the surgeon sitting in an awkward position;
2) four-dof tool motion due to the palm-on-table posture that limits tool orientation;
3) hand tremor at high image magnification;
4) no feel at all (no force feedback) at high magnification.

Telepresence-based microsurgery has the potential to provide the surgeon with a magnified workspace in which he can comfortably work with his hands on full-sized instrument handles, using normal hand motions and experiencing the feel he would expect from the magnified tissues that he sees.

2) Research at Other Institutions: Several teams are developing microtelemanipulation systems for ophthalmic surgery applications. Ophthalmic systems are characterized by a single manipulator arm with a needle-like probe without force feedback and a view of the workspace through a surgical stereo microscope. Applications include radial keratotomy [52], [53] and insertion of a hypodermic probe into retinal vessels to measure pressure and to inject drugs [54], [55]. Systems with a position-controlled master and amplified force feedback have been developed for vitreo-retinal (inner eye) surgery [56] and general eye surgery [57]. Force-amplifying micromanipulator systems employing video viewing, and hence applicable to remote operation, have demonstrated cutting a simulated, polymer eye [58] and sawing a 4-mm-diameter soft tube [59].

To date, none of the microtelemanipulation research has addressed the two-handed requirements of 1) microvascular suturing, where a needle holder is held in one hand and a pickup (forceps or tweezers) in the other, or 2) dissection, where a cutting tool is held in one hand and tension applied with the other with a pickup.

3) Work at SRI: To address the needs for performing scaled-down procedures, the TSW (with the TMIS system) has been combined with the micromanipulator RSU

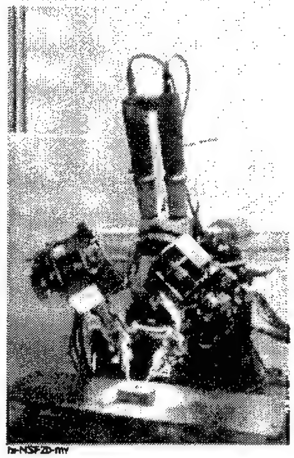


Fig. 6. Microsurgery remote surgical unit.

shown in Fig. 6. The micromanipulator RSU includes the following features:

- *slave micromanipulators:* a pair of precision manipulators without gearing on translational axes; a workspace of $100 \times 100 \times 100$ mm; continuous force of 2 N, four dof plus gripper, and a resolution of 7 μm;
- *tools:* microneedle-holder and micropickup;
- *control system:* bilateral, reduces motion scale and increases force scale, incorporates forces measured with triaxial load cells;
- *imaging:* stereo zoom microscope with three charge-coupled device (CCD) cameras mounted in eyepieces, ring light source, magnification variable from $6\times$ to $60\times$.

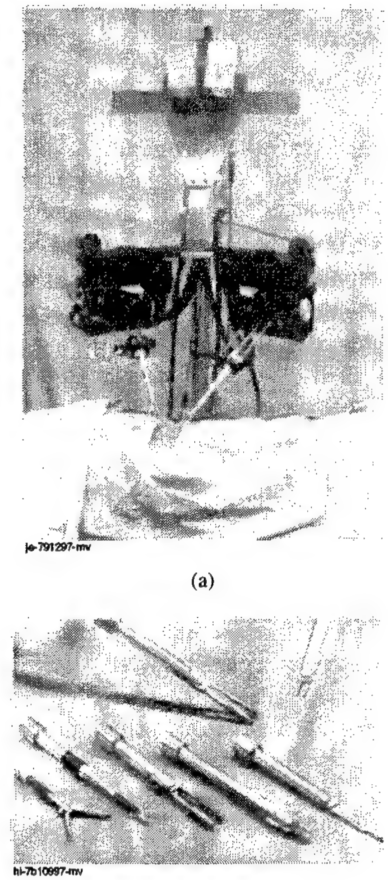
The prototype microsurgery system has been tested with *ex vivo* tasks similar to those required for surgical procedures such as cutting, grasping, suturing, and knot tying. Initial animal testing has been done on a rat model in which end-to-end anastomosis of the femoral artery (approximately 1 mm in diameter) has been completed with ten rats. Full patency was obtained in all cases.

C. Open-Surgery Demonstration System

The driving force behind military interest in remote surgery is that 90% of all deaths in wartime occur on the battlefield, before surgical care can reach the casualty. Rapid evacuation has been beneficial in decreasing the number of casualties dying of wounds after reaching a field hospital, but it has not significantly reduced the killed-in-action rate. The most likely reason that battlefield mortality remains high is that definitive surgical care is not available during the critical first hour after wounding, appropriately termed the "golden hour" by trauma surgeons.

Nonbattlefield applications of remote, open-surgery systems include the following:

- military applications (ship to ship, space station);
- civilian applications (rural intervention, remote consultation).



(a)

(b)

Fig. 7. (a) Demonstration system remote surgical unit. (b) Set of replaceable tools.

Of course, the principles of the "open-surgery" system are also applicable to nonmedical tasks such as satellite servicing, underwater science, and ocean engineering.

The SRI telepresence demonstration system [60] employs the same TSW unit as that described here for the TMIS system (see Fig. 4). The demonstration system RSU, shown in Fig. 7, includes two force-reflecting slave manipulators identical to those of the TSW except with surgical instrument tips instead of handles.

The open-surgery demonstration system RSU includes the following features:

- *manipulators:* each with a polar coordinate system with four dof (roll, pitch, yaw, and extension) with tool actuation; workspace 200 mm high and wide by 100 mm in extension; continuous force of 7 N; friction of approximately 0.3 N;
- *tools:* interchangeable needle holders, forceps (several types), graspers, and scissors, adapted from actual surgical tools, to enable a range of procedures to be performed;
- *control system:* bilateral control to scale motions and forces and incorporate forces measured with strain gauges;
- *imaging:* triple-CCD remote-head cameras with 500-mm standoff; manually operated zoom lenses and

incandescent lamps, magnification variable from half-size (0.5×) to 3×.

Using the SRI demonstration system, we have successfully performed a series of remote surgical procedures on pigs. These first ever remote surgeries included treatment of a variety of simulated abdominal and vascular injuries and were performed by surgeons experienced in trauma management. The successful results of these experiments clearly demonstrate the feasibility of telepresence surgery for emergency stabilization of battlefield casualties. In addition, project engineers closely observed the experimental procedures and held in-depth discussions with the surgeons to gain important feedback and suggestions concerning system performance and features. The results of these experiments and discussions have served as an important guide in the development of the advanced surgery system (MEDFAST).

Surgeries were performed on four- to six-month-old female Hampshire farm pigs weighing 60–80 pounds. All procedures attempted were completed successfully, including cholecystectomy, nephrectomy, repair of gastrotomy (simulated stomach injury), control of liver laceration, repair of femoral artery laceration, aortic interposition graft, and repair of bladder laceration.

The quality of the surgical procedures performed was nearly identical to that of those performed by conventional hands-on procedures, and task times were only 2.5× those of hands-on procedures [61]. Target acquisition measured using Fitts' law was about 50% slower than hands-on but about twice as fast as nonimmersive (teleoperation) interfaces [62].

D. MEDFAST Advanced Open-Surgery System

1) Advanced Telepresence Surgery System: We have developed an advanced telepresence surgery system with three components:

i) a medic-positionable RSU to be installed in an armored ambulance (the MEDFAST vehicle) with a pair of six-dof manipulators;

ii) a TSW incorporating a pair of six-dof force-reflecting hand controllers, stereo video display, patient monitor display, and other display and control devices;

iii) a low-latency, two-way, digital communication link between the RSU and the TSW.

The link includes video digitization, compression, encoding of all signals (video, servo commands, audio, patient monitoring information), and formatting of the data stream for transmission via microwave or fiber-optic links. The TSW and RSU of the MEDFAST system are illustrated in Figs. 8 and 9.

Major components of the MEDFAST system are:

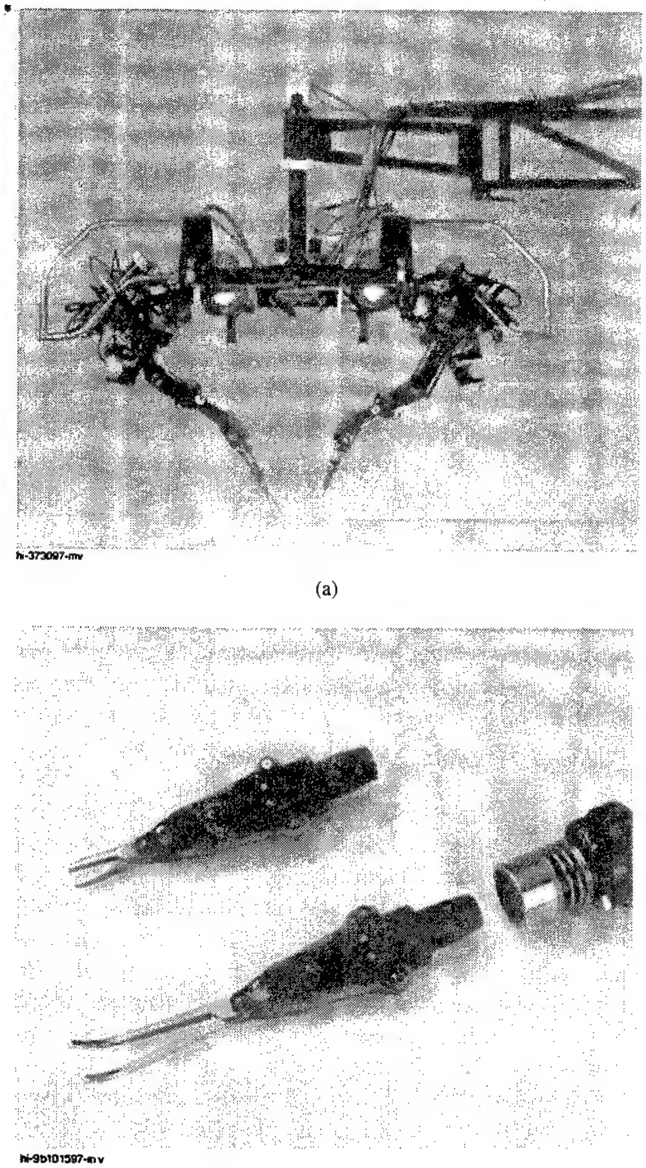
- *manipulators:* two master and two slave, each with six dof, using a three-axis wrist and single-axis elbow; push–pull tool actuation for the end effector; continuous force of 13.5 N;

Fig. 8. MEDFAST telepresence surgeon's workstation.

- *workspace:* 400 × 400 × 400 mm, with rotational motion of 360° on tool roll and yaw axis, 150° pitch axis;
- *handgrips:* pistol-grip handles with a pair of finger loops that operate proportionally;
- *tools:* manually or automatically changeable tools (scalpel, pickups, hemostat, needle holder with 200-N grip, and scissors);
- *control system:* bilateral, reduces forces on master to 50% of slave force, provision to incorporate forces measured with a triaxial load cell or six-axis load cell with through-hole for tool actuation;
- *imaging:* triple-CCD remote-head cameras with remotely operated zoom lenses and tungsten-halogen lamps, magnification variable from half-size (0.5×) to 5×, remote focus and brightness controls;
- *visual display:* 120-Hz stereo display with five-segment polarizer and passive polarized glasses;
- *panoramic display:* an additional (low-bandwidth) video camera and heads-up display to provide a panoramic view of the medic and patient inside the MEDFAST vehicle.

2) Communication Link: We have developed a two-way communication link that provides a wireless or network connection between the TSW and the RSU in the MEDFAST vehicle. The RSU communication link shown in Fig. 10 includes subsystems for digital data compression, multiplexing, and microwave or network transmission. The TSW link performs the inverse operations.

a) Video and audio subsystems: The RSU includes video cameras for the surgeon's stereo and panoramic views, and their output video streams must be digitized (via codecs) prior to radio transmission. Because the latency and



(a)

(b)

Fig. 9. (a) MEDFAST remote surgical unit. (b) Replaceable needle holder and forceps.

resolution of the surgeon's 3-D view are critical to system performance, we undertook a careful review of available video codecs. Our laboratory testing of the codecs included comparative and absolute resolution measurements using calibrated test charts and latency tests using switched diode light sources and digital timing equipment. We evaluated several high-performance codec models and found that the Alcatel model 1745 VC provided the best performance in terms of our low-latency, high-resolution requirements, in part because it performs minimal signal compression. We therefore selected the 1745 VC codec for processing the 3-D video. The 1745 VC includes a pair of high-fidelity audio subchannels that provide stereo sound feedback to the surgeon.

Latency is less of an issue for the surgeon's panoramic view, and we have chosen to compress the panoramic video (via a PictureTel PCS-100 unit) to fractional DS1

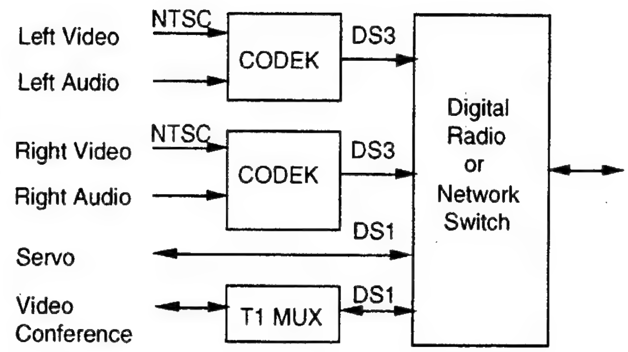


Fig. 10. RSU communication link.

bandwidth. The PCS-100 units provide duplex transmission with good image and sound quality.

b) Servo communication subsystem: Servo control data are passed between the TSW and RSU servo controllers via a DS1 channel. Full duplex position data streams, in combination with force sensor data, are sent. The hardware consists of commercial servo controller cards for 16 axes and a T1 serial port card in Pentium-based personal computer (PC) hosts at the RSU and TSW. To implement the servo communication link, we have developed real-time interface software for the host PC that transfers data between the hosts via the T1 ports and continuously monitors data integrity.

c) Radio subsystem: The radio connection between the TSW and the RSU is implemented with digital microwave radio units (Alcatel model MDR-4208e). This radio has a transmission capacity of two DS3 channels and two DS1 side channels.

We demonstrated operation of the MEDFAST surgery system with the radio link between the MEDFAST vehicle and base station on top of a nearby SRI building. Operation of the radio link was also demonstrated over 1.8 km at SRI's radio field test site in Los Banos, CA, in December 1995.

d) Network subsystem: In August 1996, operation of the existing four-dof SRI telesurgery system was demonstrated with the TSW located at Lawrence Livermore National Laboratory (Livermore, CA) and the RSU located at SRI (Menlo Park, CA). The TSW and RSU were connected via our codecs and a multiple-wavelength all-optical fiber network (including optical switches and amplifiers spanning 300 km) that was provided by the National Transparent Optical Network Consortium project at the national laboratory, funded by the Defense Advanced Research Project Agency. An additional time delay imposed by the network implementation, approximately 1–2 ms, was compensated for by increasing the lead factor in the servo algorithm. Demonstration participants were able easily and successfully to carry out remote tasks, unimpeded by the 300-km distance.

E. Testbed for Open Telepresence Surgery at the Uniformed Services University of the Health Sciences (USUHS)

The objective of this development work is to provide the Department of Defense (DOD) with a fully functional,

prototype telepresence surgical unit for use at USUHS in Bethesda, MD. This system will allow key U.S. Army, Navy, and Air Force surgeons from all surgical specialties to evaluate telepresence surgery and develop doctrine for its use. Further, the system can be used to explore methods such as surgical simulation for enhancing the core curricula of undergraduate and graduate medical education.

To accomplish these objectives, SRI has installed a six-dof MEDFAST telepresence surgery system at USUHS and is providing system maintenance and repair during the contract period. In cooperation with USUHS medical researchers, SRI is devising and conducting scientific tests to evaluate military-specific surgical applications of the system.

The objectives for the USUHS testbed project will be to:

- develop appropriate measures of surgical task performance;
- develop mission needs evaluations for DOD applications of telepresence surgery;
- evaluate the MEDFAST six-dof system and modify designs as appropriate for USUHS applications;
- initiate scientific studies of telesurgery at USUHS.

F. Surgical Simulation

1) Background: One of the significant challenges facing medicine is training for surgical procedures [63]. These tasks require cognitive, perceptual, manual dexterity, and hand–eye coordination skills. Current training practices involve hands-on training on animals and human cadavers, both of which are becoming more expensive and increasingly difficult to obtain.

Major simulation components include generation of the stereo visual image [64], force reflection on the handheld tools (haptic feedback), and synthesized sounds. Required anatomical modeling components include contact detection of tool and tissue, deformation of compliant tissue to force, and change in shape due to tearing, cutting, and puncture.

2) Research at Other Institutions: Principal work in this area has been to demonstrate environments for skill transfer using simulations based on the workbench approach. Little work has been done on training effectiveness, comparison of simulator training with hands-on procedures, or training with conventional means.

The Virtual Workbench [65] and Image Overlay systems [66] both create an immersive environment, being a mirror to map a visual onto a workspace. Neither, however, provides force feedback. The Virtual Environment Technology for Training project [67] employs a three-dof Phantom hand controller to provide force on a handheld probe.

3) Work at SRI: We have begun to develop a six-dof surgical training system using the MEDFAST TSW. The computer-generated stereo image (instead of the remote video scene) is reflected in the mirror and appears to be superimposed on the operator's hands, creating an immersive and realistic environment. Tool handles held in the user's hands are connected to left- and right-hand manipulators that each continuously measure tool position/orientation and apply reaction forces and torques to the handles, based on modeled interactions with the tool tips. Furthermore, the visual image and tool locations are carefully registered, so that the user perceives that he is looking at and moving the simulated tools in the visual image.

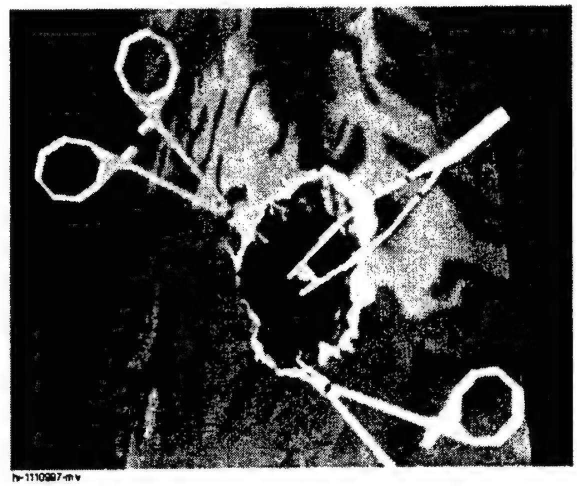


Fig. 11. Components of the SRI/MusculoGraphics wound debridement demonstration. (Courtesy of MusculoGraphics, Inc.)

SRI has been developing the hardware and software to interface the MEDFAST TSW to an SGI graphics computer for the purpose of developing a surgical simulation and training system in surgery. The training system will allow military medics and surgeons to learn "virtual" trauma management techniques for a gunshot wound to the leg, as shown in Fig. 11. The specific medical skills that will be taught include the characterization of the wound, hemorrhage control, assessment of muscle damage, intravenous insertion, and debridement. The graphics for the leg simulation will use a software simulation model developed by MusculoGraphics, Inc., Evanston, IL. Force feedback is provided by the force reflection hardware and software used in the SRI telemanipulation systems and is based on servo control digital signal-processing hardware. The scope of the simulation includes selection and motion of two tools, contact detection between tool and object, and one deformable object (the leg).

IV. Conclusions

As a result of the care we have taken to make our telepresence systems closely duplicate the operator's direct visual, tactile, and aural experience, we have developed an effective remote manipulation environment with a compelling sense of realism. The images of the slave instruments as seen by the operator are congruent with the master controls, and the slave manipulators are seen to follow the operator's hand motions precisely.

We have so far been able to develop telepresence technology to the point that our prototype four-dof TMIS system can speed the performance of complex surgical tasks by about 30% relative to manual techniques while reducing operator stress and improving performance.

In the areas of microsurgery and remote open surgery, we have demonstrated excellent technical proficiency and tremor elimination with our telepresence systems, but procedures are still about two to three times slower than direct hands-on performance. Considering, however, that our systems currently have fewer degrees of freedom, less bandwidth, and more friction and inertia than the human hand, there is considerable opportunity to reduce the performance gap.

Thus, when the surgical site to be treated is deep within a patient's body where our hands cannot reach, is too small and delicate for direct hands-on work, or is remotely located on a space station or at sea, telepresence technology has the potential to provide a unique solution.

REFERENCES

[1] R. Goertz, J. Grimson, C. Potts, D. Mingesz, and G. Forster, "ANL mark E4A electric master-slave manipulator," in *Proc. 14th Conf. Remote Systems Tech.,* 1966, pp. 115–123.

[2] C. R. Flatau, "Compact servo master-slave manipulator with optimized communication links," in *Proc. 17th Conf. Remote Systems Tech.,* 1969, pp. 154–164.

[3] J. Vertut and P. Coiffet, *Robot Technology Series,* vols. 3A and B, *Teleoperation and Robotics.* Englewood Cliffs, NJ: Prentice-Hall, 1986.

[4] T. B. Sheridan, *Telerobotics, Automation, and Human Supervisory Control.* Cambridge, MA: MIT Press, 1992.

[5] P. Dario, E. Guglielmelli, and B. Allotta, "Robotics in medicine," in *Proc. IEEE/RSJ Int. Conf. Intelligent Robots and Systems (IROS'94),* Munich, Germany, Sept. 12–16, 1994, vol. 2, pp. 739–752.

[6] E. Ernst and K. Adlassnig, "Robotics in medicine: A brief survey," in *Proceedings of Medical Informatics,* K.-P. Adlassnig, G. Grabner, S. Bengtsson, and R. Hansen, Eds. Berlin, Germany: Springer-Verlag, 1991, pp. 1032–1036.

[7] K. Masamune, M. Sonderegger, H. Isek, K. Takakura, M. Suzuki, and T. Dohi, "Robots for stereotactic neurosurgery," *Advanced Robotics,* vol. 10, no. 4, pp. 391–401, 1996.

[8] R. H. Taylor, B. D. Mittelstadt, H. A. Paul, W. Hanson, P. Kazanzidas, J. F. Zuhars, B. Williamson, B. L. Mustis, E. Glassman, and W. L. Bargar, "An image-directed robotic system for precise orthopaedic surgery," *IEEE Trans. Robot. Automat.,* vol. 10, no. 3, p. 261, 1994.

[9] W. S. Ng, B. L. Davies, R. D. Hibberd, and A. G. Timoney, "Robotic surgery: A first-hand experience in transurethral resection of the prostate," in *Proc. IEEE Engineering in Medicine and Biology,* 1993, pp. 120–125.

[10] M. W. Thring, *Robots and Telechirs.* Chichester, U.K.: Ellis Horwood, 1983.

[11] K. Marsuhima and H. Koyanagi, "Servo micromanipulator 'Tiny-Micro Mk. I,'" in *Proc. 4th CISM-IFToMM Symp.,* Zaborow, Poland, Sept. 8–12, 1981, p. 251.

[12] M. Sabatini, M. Bergamasco, and P. Dario, "Force feedback-based telemicromanipulation for robot surgery on soft tissues," in *Proc. IEEE Engineering in Medicine and Biology, 11th Ann. Int. Conf.,* 1989, pp. 890–891.

[13] S. Nakaura, T. Hoshino, H. Tokura, and M. Yoshikawa, "Development of a bilateral manipulator for surgical operation—Characteristics of developed manipulator," *J. Jpn. Soc. Precis. Eng.,* vol. 62, no. 10, pp. 1449–1453, Oct. 1996.

[14] A. D. Alexander, "Impacts of telemation on modern society," in *Proc. 1st IFToMM Symp.,* vol. 2, p. 122, 1978.

[15] P. S. Green, J. W. Hill, and R. M. Satava," Telepresence: Dexterous procedures in a virtual operating field (abstract)," *Surgical Endoscopy,* vol. 57, p. 192, 1991.

[16] S. Charles, R. E. Williams, and B. Hamel, "Design of a surgeon–machine interface for teleoperated microsurgery," in *Proc. IEEE Engineering in Medicine and Biology, 11th Ann. Int. Conf.,* 1989, pp. 883–884.

[17] D. B. Diner and D. H. Fender, *Human Engineering in Stereoscopic Viewing Devices.* New York: Plenum, 1993.

[18] S. Charles "Dexterity enhancement for surgery," in *Proc. 1st Int. Symp. Medical Robotics and Computer Assisted Surgery,* Pittsburgh, PA, Sept. 22–24, 1994, pp. 145–160.

[19] W. Brook and D. P. Hannema, "Master–slave manipulator performance for various dynamic characteristics and positioning task parameters," *IEEE Trans. Syst., Man., Cybern.,* vol. 10, pp. 764–771, 1990.

[20] M. Uebel, M. Ali, and I. Minis "The effect of bandwidth on telerobot system performance," *IEEE Trans. Syst., Man, Cybern.,* vol. 24, no. 2, pp. 342–348, 1994.

[21] J. R. Burnett, "Force-reflecting servos add 'Feel' to remote controls," *Control Eng.,* pp. 82–87, July 1957.

[22] A. K. Bejczy and M. Handlykken, "Generalization of bilateral force-reflecting control of manipulators," in *Proc. 4th Int. CISM-IFToMM Symp.,* Zaborow, Poland, Sept. 8–12, 1981, pp. 242–255.

[23] W. S. Kim, "Developments of new force reflecting control schemes and an application to a teleoperation training simulator," in *Proc. 1993 IEEE Int. Conf. Robotics and Automation,* Nice, France, 1992, pp. 1412–1419.

[24] Y. Yokokohji and T. Yoshikawa, "Bilateral control of master–slave manipulators for ideal kinesthetic coupling-formulation and experiment," *IEEE Trans. Robot. Automat.,* vol. 10, no. 5, pp. 605–620, 1994.

[25] G. J. Raju, "Operator adjustable impedance in bilateral remote manipulation," Ph.D. dissertation, Man-Machine Systems Laboratory, Massachusetts Institute of Technology, Cambridge, 1988.

[26] N. Hogan, "Controlling impedance at the man/machine interface," in *Proc. IEEE Int. Conf. Robotics and Automation,* Scottsdale, AZ, 1989, pp. 1626–1631.

[27] C. L. Moore and H. Kazerooni, "Bilateral impedance control for telemanipulators," in *Proc. Japan-USA Symp. Flexible Automation,* San Francisco, CA, July 13–15, 1992, pp. 1–7.

[28] J. E. Colgate, "Robust impedance shaping telemanipulation," *IEEE Trans. Robot. Automat.,* vol. 9, no. 4, pp. 374–384, 1993.

[29] H. Kazerooni, "Human/robot interaction via the transfer of power and information signals," in *Proc. IEEE Int. Conf. Robotics and Automation,* Scottsdale, AZ, 1989, pp. 1632–1649.

[30] P. A. Millman and J. E. Colgate, "Design of a force reflecting manipulandum with a specified force/torque workspace," in *Proc. 1991 IEEE Int. Conf. Robotics and Automation,* vol. 2, pp. 1488–1493.

[31] N. Hogan, "On the stability of manipulators performing contact tasks," *IEEE J. Robot. Automat.,* vol. 4, no. 6, pp. 677–686, 1988.

[32] N. Hogan and J. E. Colgate, "Stability problems in contact tasks," in *Robotics Review,* J. J. Craig, O. Khatib, and T. Lozano-Perez, Eds. Cambridge, MA: MIT Press, 1989, pp. 339–348.

[33] R. J. Anderson and M. W. Spong, "Bilateral control of teleoperators with time delay," *IEEE Trans. Automat. Contr.,* vol. 34, no. 5, 1989, pp. 494–501.

[34] J. E. Colgate, "Coordinate transformations and logical operations for minimizing conservativeness in coupled stability criteria," *J. Dynamic Syst., Measure., Control,* vol. 116, pp. 643–649, 1994.

[35] ——, "Coupled stability of multiport systems—Theory and experiments," *J. Dynamic Syst., Measure., Control,* vol. 116, pp. 419–428, 1994.

[36] ——, "Power and impedance scaling in bilateral manipulation," in *Proc. 1991 IEEE Int. Conf. Robotics and Automation,* 1991, pp. 2292–2297.

[37] P. M. Fitts, "The information capacity of the human motor system in controlling amplitude of movement," *J. Experimental Psych.,* vol. 47, pp. 381–391, 1954.

[38] J. W. Hill and S. J. Matthews, "Modeling a manipulation task of variable difficulty," in *Proc. 12th Ann. Conf. Manual Control,* University of Illinois, Urbana, IL, May 1976, pp. 639–660.

[39] J. W. Hill and K. Salisbury, "Study to design and develop remote manipulator systems," *Quarterly Reports 7 and 8,* NASA, SRI International, Menlo Park, CA, SRI Project 8652, Nov. 1977.

[40] J. W. Hill, "Two measures of performance in a peg-in hole manipulation task with force feedback," in *Proc. 13th Ann. Conf. Manual Control,* Massachusetts Institute of Technology, Cambridge, June 1977.

[41] ——, "Study of modeling and evaluation of remote manipula-

tion tasks with force feedback," SRI International, Menlo Park, CA, Final Rep., JPL Contract 95-5170, 1979.
[42] L. B. Rosenberg, "The effect of interocular distance upon depth perception when using stereoscopic displays to perform work within virtual and telepresent environments," student paper, Dept. Mechanical Engineering, Stanford University, Stanford, CA, June 1, 1992.
[43] T. B. Sheridan, *Telerobotics, Automation, and Human Supervisory Control.* Cambridge, MA: MIT Press, 1992.
[44] J. Funda, R. Taylor, S. Gomory, B. Eldridge, K. Gruben, and M. Talamini, "An experimental user interface for an interactive surgical robot," in *Proc. 1st Int. Symp. Medical Robots and Computer Assisted Surgery,* Pittsburgh, PA, Sept. 1994, pp. 196–203.
[45] J. Funda, R. Taylor, B. Eldridge, S. Gomory, K. Gruben, and M. Talamini, "Constrained Cartesian motion control for teleoperated surgical robots," *IEEE Trans. Robot. Automat.,* vol. 12, pp. 453–465, June 1996.
[46] D. R. Uecker, C. Lee, Y. F. Wang, and Y. Wang, "A speech directed multi-modal man-machine interface for robotically enhanced surgery," in *Proc. 1st Int. Symp. Medical Robots and Computer Assisted Surgery,* Pittsburgh, PA, 1994, pp. 176–183.
[47] N. J. Dowler and S. R. J. Holland, "The evolutionary design of an endoscopic telemanipulator," *IEEE Robot. Automat. Mag.,* pp. 38–45, Dec. 1996.
[48] B. Neisius, P. Dautzenberg, R. Trapp, and G. Buess, "Robotic manipulator for endoscopic handling of surgical effectors and cameras," in *Proc. 1st Int. Symp. Medical Robotics and Computer Assisted Surgery,* Pittsburgh, PA, 1994, pp. 169–175.
[49] J. Jensen, J. Hill, and R. Li, "Telepresence surgery," presented at Medicine Meets Virtual Reality, San Diego, CA, Jan. 22–25, 1997.
[50] S. Charles, "Dexterity enhancement for surgery," in *Proc. 1st Int. Symp. Medical Robotics and Computer Assisted Surgery,* Pittsburgh, PA, Sept. 22–24, 1994, pp. 145–160.
[51] R. Franken, S. C. Gupa, S. R. Rod, S. V. Thomas, J. H. Barker, M. Kon, and J. C. Banis, "Microsurgery without a microscope: Development of a three-dimensional on-screen microsurgery system (TOMS)," *J. Med. Virtual Reality,* vol. 1, no. 1, pp. 26–32, 1995.
[52] A. Guerrouad and P. Vidal, "SMOS: Stereo-telemanipulator for ocular surgery," in *Proc. IEEE Engineering in Medicine and Biology, 11th Ann. Int. Conf.,* 1989, pp. 879–880.
[53] S. Hayat and P. Vidal, "Conception of information tools to assist the surgeon when he carries out radial keratotomy with a microtelemanipulator," in *Proc. 1st 1995 Regional Conf. IEEE Engineering in Medicine and Biology Society and 14th Conf. Biomedical Engineering Society of India,* New Delhi, India, 1995, pp. 3.5–3.6.
[54] P. A. Millman and J. E. Colgate, "Design of a force reflecting manipulandum with a specified force/torque workspace," in *Proc. 1991 IEEE Int. Conf. Robotics and Automation,* vol. 2, pp. 1488–1493.
[55] P. S. Jensen, M. R. Glucksbergh, J. E. Colgate, K. W. Grace, and R. Attarwala, *Proc. 1st Int. Symp. Medical Robotics and Computer Assisted Surgery,* Pittsburgh, PA, 1994, pp. 204–210.
[56] P. S. Schenker, H. Das, and T. R. Ohn, "Development of a master–slave manipulator for dexterity enhancement microsurgery," in *Proc. SPIE: Telemanipulator and Telepresence Technologies,* H. Das, Ed., Boston, MA, vol. 2351, Oct. 1994.
[57] W. E. Ford, A. K. Morimoto, D. M. Kozlowski, and S. T. Charles, "Micro-telerobotic applications for microsurgery," in *Int. Association of Science and Technology for Development Conf. Robotics and Manufacturing,* Cancun, Mexico, June 14–17, 1995, Rep. SAND-95-1123C; CONF-9506178-2.
[58] I. W. Hunter, T. D. Doukoglou, L. A. Jones, P. G. Charette, M. A. Sagar, G. D. Mallinson, and P. J. Hunter, "A teleoperated microsurgical robot and associated virtual environment for eye surgery," *Presence,* vol. 2, no. 4, pp. 265–280, 1993.
[59] M. Mitsuishi, T. Watanabe, H. Nakanishi, T. Hori, R. Asai, and H. Watanabe, "Tele-micro-surgery system that shows what the user wants to see," in *Proc. IEEE Int. Workshop on Robot and Human Communication,* 1995, pp. 237–246.
[60] J. W. Hill, J. F. Jensen, P. S. Green, and A. S. Shah, "Two-handed telepresence surgery demonstration system," in *Proc. ANS 6th Ann. Topical Meeting on Robotics and Remote Systems,* Monterey, CA, Feb. 5–10, 1995, vol. 2, pp. 713–720.
[61] J. C. Bowersox, A. Shah, J. F. Jensen, J. Hill, and P. Cordts, "Vascular applications of telepresence surgery: Initial feasibility studies in swine," *J. Vascular Surgery,* vol. 1, no. 23, pp. 281–287, 1996.
[62] R. Li, J. Bowersox, J. Hill, A. Shah, and K. Workman, "Evaluation of an immersive telepresence interface for surgical tasks performance," presented at Medicine Meets Virtual Reality, San Diego, CA, Jan. 22–25, 1997.
[63] R. M. Satava, "Emerging medical applications of virtual reality: A surgeon's perspective," *Artificial Intell. Med.,* vol. 6, no. 4, pp. 281–288, Aug. 1994.
[64] N. Ayache, "Medical computer vision, virtual reality and robotics," *Image and Vision Computing,* vol. 13, no. 4, pp. 295–313, 1995.
[65] T. Poston and L. Serra, "Dexterous virtual work," *Commun. ACM,* vol. 39, no. 5, pp. 37–45, May 1996.
[66] M. Blackwell, R. V. O'Toole, F. Morgan, and L. Gregor, "Performance and accuracy experiments with 3D and 2D image overlay systems," in *Proc. 2nd Medical Robotics and Computer Assisted Surgery (MRCAS'95)* Baltimore, MD, Nov. 5–7, 1995, pp. 312–317.
[67] N. Durlach. (1997). The RLE virtual environment technology for training virtual workbench. [Online]. Available: http://mimsy.mit.edu/people/tew/VWBpage.hmtl.

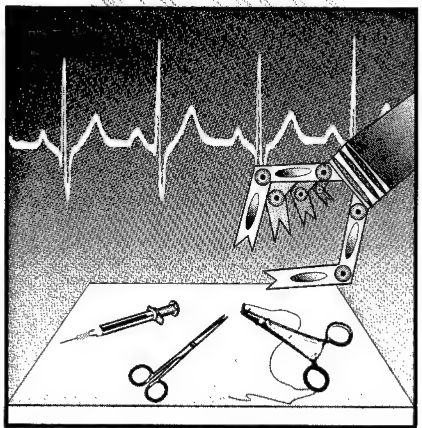
John W. Hill (Member, IEEE) received the B.S. and M.S. degrees in electrical engineering from the University of Illinois, Urbana, in 1961 and 1963, respectively, and the Ph.D. degree in electrical engineering from Stanford University, Stanford, CA, in 1967.

He has been with SRI International, Menlo Park, CA, three times since 1967, with SRI's Bioengineering Group, Artificial Intelligence Center, and Robotics and Machine Vision Group. In 1980, he left SRI to found Microbot, Inc., and serve as the Developer of the company's robotic product line. He currently is with SRI's Medical Technology Program. His current research interests include telepresence, man–machine integration, and medical manipulators for surgery.

Dr. Hill is Chairman of the San Francisco Bay Area IEEE-EMBS chapter.

Joel F. Jensen received the B.S.M.E. degree from Ohio University, Athens, in 1981 and the M.S.E.E. degree from Santa Clara University, Santa Clara, CA, in 1991.

He has led major product-development projects in the areas of medical imaging and drug delivery and has served as a Consultant to clients of SRI International, Menlo Park, CA, in the areas of medical products and markets. He is an expert in the development of complex, precision, servo-controlled electromechanical systems and has been working in the telepresence field since 1991. He currently is Principal Investigator for the ongoing Defense Advanced Research Project Agency telesurgery project at SRI. Prior to joining SRI in 1983, he supervised a Mechanical Design Group at Southwall Corporation, a manufacturer of optically coated films.



Telepresence Surgery

P.S. Green, J. W. Hill, J.F. Jensen, and A. Shah
SRI International, Menlo Park, CA

Medicine is entering a period of profound technological transition, driven by the need to provide improved care to more people at lower cost. Two of the key developments in this transformation are minimal-access surgery and telemedicine. SRI International has developed technology that significantly enhances both of these developments.

Minimal-access surgery, sometimes called minimally invasive or "closed" surgery, encompasses a wide range of procedures that are performed without major incisions. One of these, laparoscopic surgery, has proved especially effective at improving medical outcomes while reducing the lengths of hospital stay and recovery, consequently reducing cost. However, the range of laparoscopic procedures that can be performed by most general surgeons is limited by the awkwardness of maneuvering the long instruments, which are fulcrumed in the abdominal wall, and the poor eye-hand coordination afforded by the video display, which is typically positioned across the operating table. By making laparoscopic and other closed surgeries look and feel like familiar "open" surgery, SRI's Telepresence technology significantly expands the number and variety of procedures that can be performed as closed surgery.

In telemedicine, thus far, most advances have been diagnostic—for example, reading x-rays at a remote medical center or mentoring local physicians as they examine patients. In the future, Telepresence will enable expert surgeons at regional medical centers to actually participate in surgeries at local clinics.

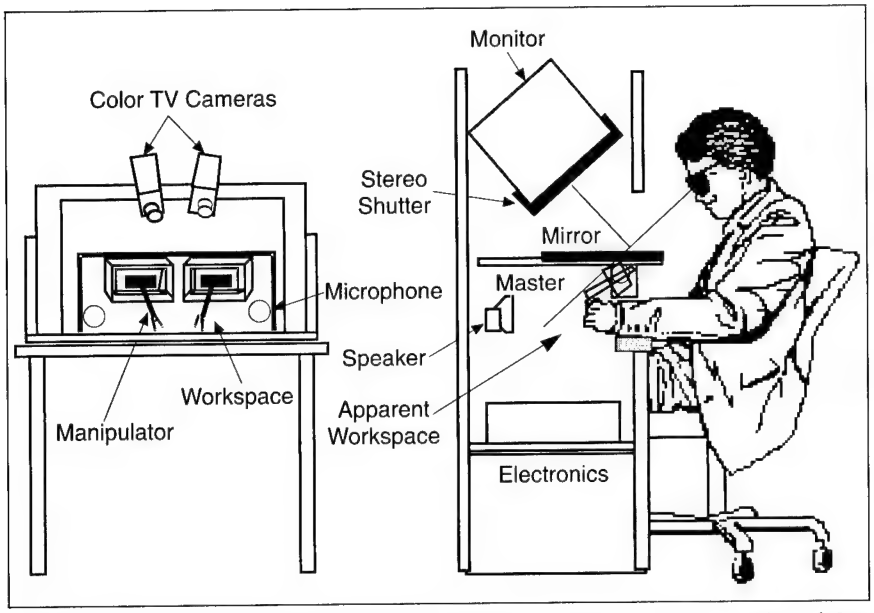
Teleoperation, or remote manipulation, has been in use for many years—for example, to handle radioactive materials. The application of teleoperation to surgery has been anticipated and experimented with for some time [1-4]. However, in its conventional form, teleoperation does not provide an interface natural enough to enable surgeons to operate in the deft manner to which they are accustomed. Telepresence is enhanced teleoperation; the operator perceives that the remote worksite is directly in front of him or her. The Telepresence surgeon effectively uses surgical instruments that may actually be located in a remote operating room. Grasping these instruments, the surgeon looks and reaches into the remote surgical site and carries out the operation, feeling the resistance of the tissues as they are touched by the instruments and feeling the suture as a knot is tied, just as he would in a conventional operation [5]. In SRI's Telepresence system, the unique integration of specially developed surgical telemanipulators, feedback control systems that provide touch sensitivity, and stereographic video provides an experience so compellingly real that, without special instruction or training, surgeons can carry out remote surgical procedures with speed, precision, and agility [6, 7, 8]. Using the system's special laparoscopic manipulators, difficult minimal-access surgery can be performed with relative ease, with techniques similar to those of conventional open surgery. The SRI system differs from surgical robots, which are preprogrammed and move autonomously [9-11], in that the surgeon precisely controls every movement of the remote manipulators. Unlike other surgical telemanipulators recently demonstrated [12, 13], which focus mainly on the manipulator, we have developed a complete surgical system integrating vision, hearing, and manipulation.

The System

SRI's Telepresence Surgery System consists of two main modules: a surgeon's console, and a remote surgical unit (RSU) located at the surgical table. As shown in Fig. 1, the surgeon sits at the console and looks down into the surgical field, a "virtual workspace" recreated by a special arrangement of a 120-field/s stereographic video monitor with a liquid -crystal shutter (the operator wears passive polarized glasses) and a mirror. The stereographic video is generated by a pair of video cameras in the RSU; they are positioned over the patient in special relationship to the surgical manipulators. In the laparoscopic version, a stereo laparoscope (available from several manufacturers) is substituted for the camera pair.

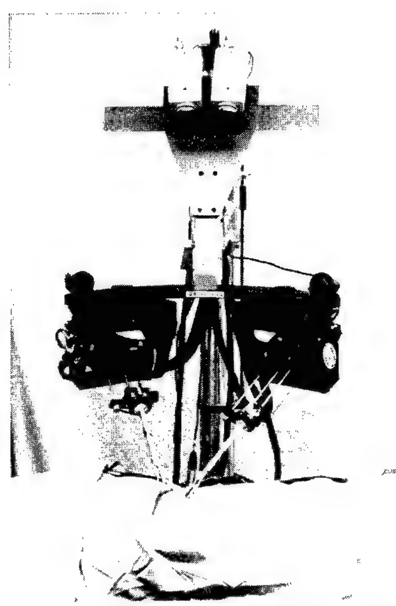
As shown in Fig. 2, the surgeon reaches under the mirror and grasps two surgical-instrument handles (hemostats with the latches and jaws removed) that operate two master manipulators. Each master directs the movement of a slave manipulator at the RSU, shown in Fig. 3, by means of a highly responsive, force-reflecting

 0739-5175/95/$4.00©1995



1. Surgeon looks down into the apparent workspace, a stereo-video recreation of the actual workspace at the left. The remote manipulators appear to emerge from the hand controls, which are not seen by the surgeon. The master and slave move in perfect synchrony and reflect forces realistically.

2. The latest surgeon's console provides two hand-control masters with surgical-instrument handles, a stereographic view into the surgical site, and a microphone and speakers for communicating with the surgical assistant or nurse in the operating room. Looking straight ahead, the surgeon sees a panoramic view across the table, on three side-by-side LCDs.



3. The remote surgical unit (RSU) comprises two slave manipulators with interchangeable surgical instruments, two video cameras positioned correctly with respect to the manipulators and canted in for stereo convergence in the middle of the operating field, microphones, and a trio of video cameras (not shown) that produce a panoramic view of the operating room from the surgeon's perspective.

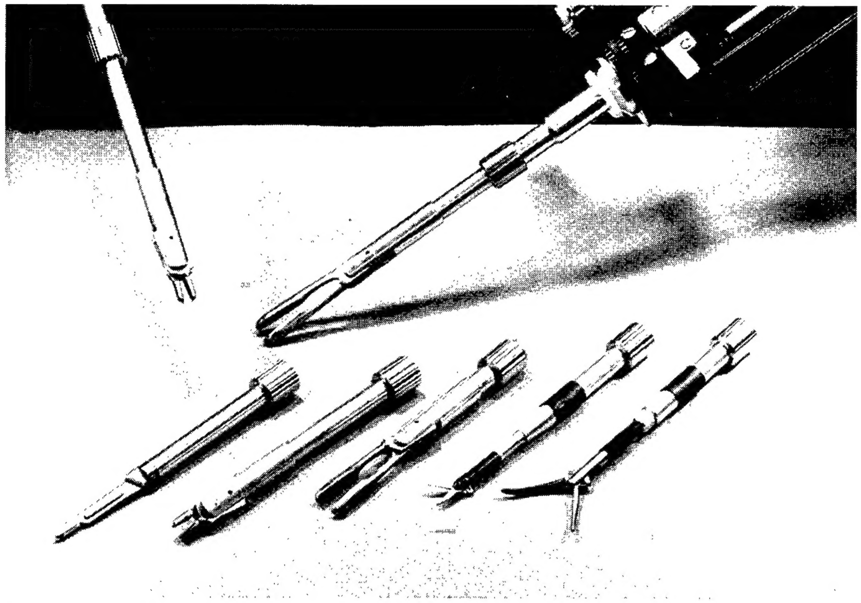
servo-controller. Affixed to the ends of the manipulator arm are interchangeable surgical instruments—forceps, needle drivers, bowel graspers, scalpels, and cautery tips, as shown in Fig. 4. The surgeon sees the instruments in the stereographic image—they appear to be emerging from the handles in his hands. When he moves his hand controls, the instruments move as if they were rigidly attached to the controls. Sounds from the instruments or the surgeon's assistants are picked up by stereo microphones and relayed to speakers in the surgeon's console. To the surgeon, it looks and feels (and sounds) as if he is performing the task right before his eyes with conventional surgical instruments in his hands. The strength of this perception enables the surgeon to carry out complex tasks with quick, precise motions.

The masters and slaves are lightweight, responsive, well-balanced, and gravity-compensated. Friction has been minimized by reducing the stages of gearing, using low-friction/low-inertia actuators, and using low-friction bearings throughout. The usual drawbacks of inertia and friction—degraded operator performance and fatigue after prolonged use—have been largely eliminated. The bilateral control system provides for scaled motion and force reflection, which, along with scaled video, enable the surgeon to perform microsurgery with normal hand motions. The current open-surgery manipulators have five degrees of freedom, with force feedback in each axis (including opening and closing the jaws of graspers or scissors). More dexterous manipulators and many other improvements are being incorporated into the system for specific applications, as described below.

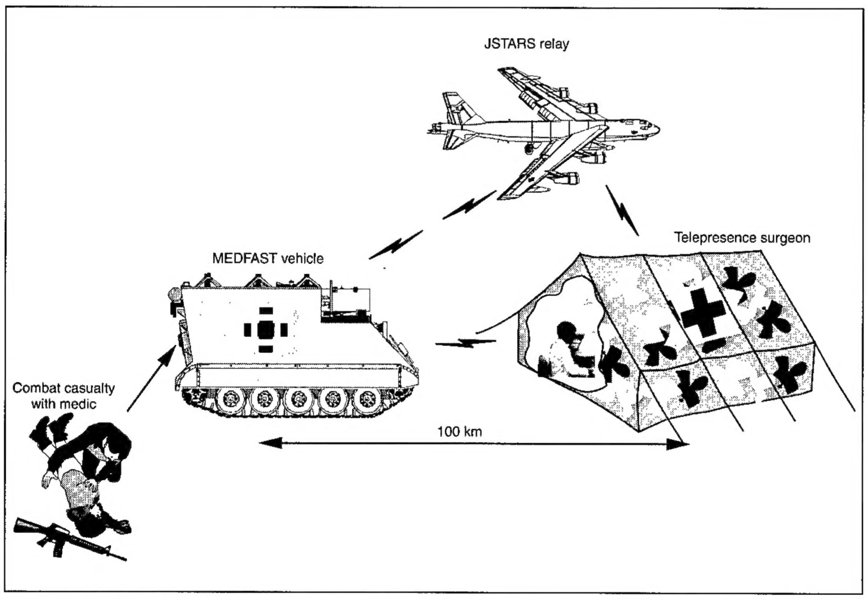
Remote Surgery on the Battlefield

Potentially, Telepresence surgery can make a significant contribution to the management of combat trauma. Nine out of ten combat-related deaths from nonfatal injuries occur in the combat zone, prior to evacuation, the majority from loss of blood. Many of these lives could be saved if surgical treatment were available within one hour of injury—dubbed the "Golden Hour" by Army Surgeon General Alcide Lanoue. However, in modern warfare, the front line may move forward so quickly that mobile army surgical hospitals (MASH units) cannot get established close enough to the combat zone to be effective. Currently, the only care available to the seriously wounded soldier within the combat zone is that provided by the field medic, whose goal is to stabilize him and prepare the victim for evacuation [14].

To provide surgical services in the zone of combat, SRI is developing a battlefield version of its Telepresence Surgery System. This version has been installed in a mobile surgical vehicle, dubbed the medical emergency forward area surgical telepresence (MEDFAST), envisioned to be deployed as illustrated in Fig. 5. After first aid has been administered by the medic, the wounded soldier in need of immediate surgery is



4. An array of interchangeable surgical instruments.



5. From a position safely behind the lines, the Telepresence combat surgeon of the future will carry out surgeries in mobile surgical vehicles operating throughout the zone of combat, with the assistance of medics assigned to each vehicle. First field tests will employ a point-to-point microwave link to carry video, servo, audio, and patient monitoring information, which eventually may be relayed by low-earth-orbit satellites.

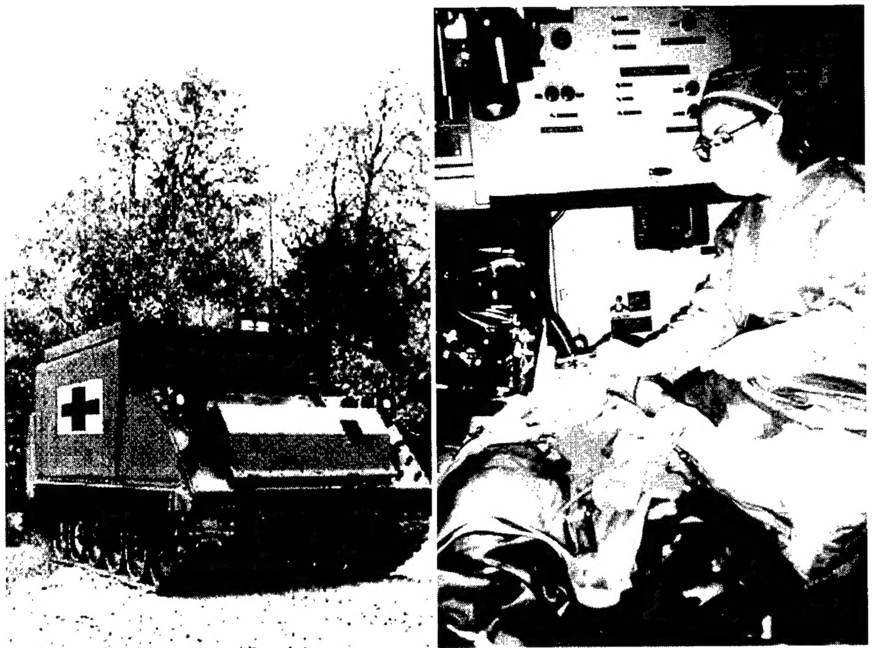
brought to the MEDFAST and put on the operating table. The Telepresence combat surgeon carries out only a limited spectrum of procedures. These are primarily for stabilizing wounded soldiers, so that they can be evacuated when conditions permit, and for treating conditions that, if deferred, would seriously affect recovery. The most threatening conditions are airway obstructions, sucking chest wounds, and profuse bleeding. The surgeon can remotely explore for and repair injuries to major vessels and abdominal and pelvic organs, remove bone fragments and foreign material, and debride damaged tissues. The wound can then be packed and dressed; wound closure is left to the next echelon of care. Telepresence surgery greatly augments the trauma care that the medic alone can provide.

This concept was demonstrated in June 1993 during a medical field exercise held at Ft. Gordon in Augusta, GA. In a tent, Army surgeons, seated at an early version of our console operated on an "injured soldier"—actually, a life-like mannequin with pig intestines in its abdominal cavity. A medic at the patient's side assisted the surgeon. The patient, the RSU, and the medic were located in a transportable operating room (OR) 30 meters from the tent. Cables carried the control, video, and audio signals between the units (a high-bandwidth, two-way radio link would be required in an actual combat situation). At Ft. Gordon, only a single master-slave combination was used; nevertheless, the potential was evident and the surgeons were enthusiastic.

Encouraged by the Ft. Gordon results, we began preparation for a much more realistic demonstration, in which two-handed surgery would be carried out in a combat-ready vehicle outfitted as a mobile OR. The new surgeon's console (Fig. 2) was constructed and outfitted [15]. This version incorporates two hand-control masters with surgical-instrument handles, a stereographic monitor viewed with a mirror, a microphone and speakers for communicating with the surgical assistant or nurse in the OR, and three side-by-side liquid crystal displays (LCDs) that provide a panoramic view across the operating table, allowing the surgeon to see the medic and any activity in the OR. The new OR, a 577 tracked, armored vehicle, was equipped with a special operating table, an electrically controlled gantry for positioning the RSU over the patient, and other equipment, as shown in Fig. 6.

This equipment was transported to Washington, D.C., in October 1994, and demonstrated at the annual convention of the Association of the U.S. Army. Still linked by a cable, the two units were situated 160 meters apart—the 577 in the hotel parking lot and the surgeon's console in a third-floor exhibition hall. On the operating table lay a soldier mannequin with lacerated pig intestines and liver in its abdominal cavity, along with bits of shrapnel, and a simulated bleeding artery squirting blood (activated surreptitiously by the medic). This is representative of the type of abdominal wound suffered in combat [16].

Surgeons, and many others, had the opportunity to sit at the console, suture the lacerations, remove shrapnel, and expose the "bleeder," which the medic then clamped. Surgeon and medic worked together as if they were standing across the table from each other. For example, the medic passed the suture to the surgeon and then provided countertension on the tissues while the surgeon sewed. Surgeons



(a) (b)

6. Operating room in a tracked, armored vehicle. (a) The XM577A3 armored tactical command and control system vehicle, which was modified for this project by Foster-Miller, Inc., in cooperation with United Defense Limited Partnership, (b) interior of the 577, showing the operating table, surgical manipulators, cameras and lights, the medic, and auxiliary surgical and support equipment. The "patient" was a dummy with pig intestines, shrapnel, and a simulated bleeding artery in its abdominal cavity.

were able to run suture lines and do instrument ties with high dexterity and speed.

The general consensus was that the feasibility of Telepresence surgery on the battlefield had been demonstrated, although a number of improvements were needed. Preparation of the system has begun for actual field trials. Three notable features are being added: (1) a pair of seven-degree-of-freedom hand controls and manipulators, (2) a wireless communication system, and (3) a broader array of surgeon-interchangeable instruments.

Telepresence Laparoscopic Surgery

Laparoscopic surgery has almost totally replaced open surgery for cholecystectomy (gallbladder removal). However, few surgeons are able to progress to more complex laparoscopic procedures, such as bowel and esophageal surgery, because of the inadequacy of current instrumentation. In the U.S. alone, there are perhaps four million open surgical procedures performed each year that could be converted to closed procedures if better surgical technology were available. The benefits would be substantial, as has been demonstrated for cholecystectomy: lower costs, shorter hospital stays, much quicker recovery, less infection, and less cosmetic damage. The problem: laparoscopic surgery entails awkwardly maneuvering long instruments that are inserted through cannulae in the abdominal wall. The wall acts as a fulcrum, so that the direction of motion of the instrument tip is opposite that of the surgeon's hand, and the magnitude of the tip motion depends on the extent to which the instrument has been inserted. The surgeon watches the instrument tip and the internal organs on a video screen across the OR table, an arrangement that makes eye-hand coordination extremely difficult. This combination of activities is totally unnatural; every motion must be deliberate (rather than spontaneous, as it is in open surgery). Moreover, the instruments provide little force feedback, which is very important to the surgeon. The combined effect is to make suturing, knot tying, and many other usually simple maneuvers exceedingly difficult to do laparoscopically.

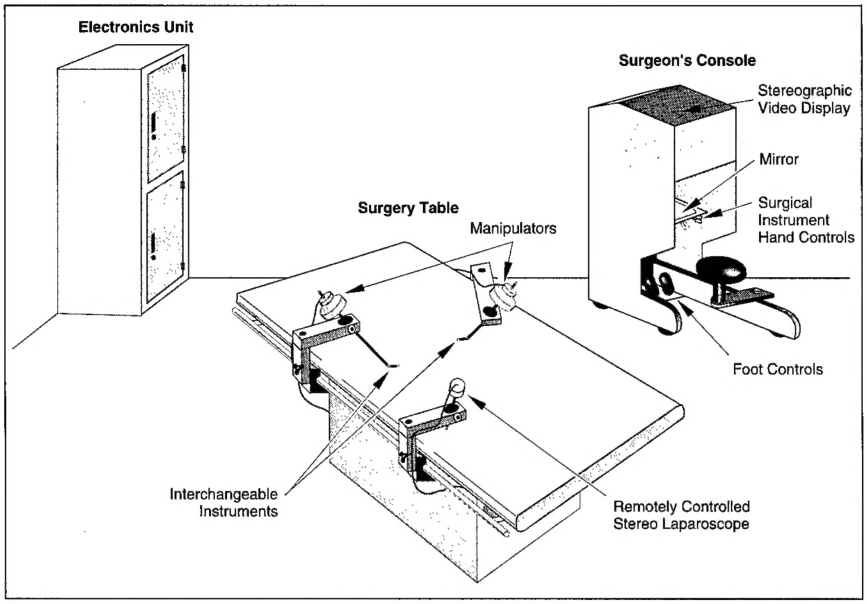
Telepresence overcomes these barriers to effective laparoscopic surgery. Although SRI's Telepresence-operated laparoscopic instruments (as also conventional laparoscopic instruments) are inserted through cannulae in the abdominal wall, the surgeon's perception is that of using the traditional instruments in an open surgical field. The Telepresence laparoscopic surgeon grasps the open-surgery instrument handles, looks down into the actual surgical field (via a 3-D video laparoscope), and operates. Now, his hands are effectively inside the abdomen, on the correct side of the fulcrum. The instrument tips, as viewed by the surgeon, move as if they were rigidly connected to the handles in his hands. As the instruments touch tissue, the surgeon feels the resistance through the handle. Unlike conventional laparoscopic surgery, which requires extensive additional training and continued practice, Telepresence surgery thus requires little additional training.

Preliminary dexterity experiments involving simple maneuvers, such as transferring beads from wire to wire and cannulizing one plastic tube with another, have also been conducted. Comparisons were made between (1) free-hand operation using a hemostat, (2) the use of a conventional fulcrumed laparoscopic grasper viewed with a monoscopic video laparoscope, and (3) Telepresence operation, using an open-surgery Telepresence manipulator with both monoscopic and stereoscopic viewing [17]. The results confirmed expectations. Three subjects took 7 to 15 times longer with the conventional laparoscopic instruments than with Telepresence; in these tests, the latter was almost as effective as free-hand manipulation. SRI's laparoscopic Telepresence equipment is now undergoing evaluation in animal surgery.

Telepresence laparoscopic surgery will result in significantly lower health care costs. OR time for complex procedures such as colon resections and other bowel surgeries, Nissen fundoplication, and laparoscopically assisted vaginal hysterectomy will be only marginally higher than those of an open procedure—much less than for laparoscopic surgery as currently practiced. Costs associated with the hospital stay and return to normal function will be the same as for current laparoscopic procedures—much lower than for open surgery. Telepresence laparoscopic surgery should combine the best of both worlds. It is expected that patient demand will drive the adoption of other laparoscopic procedures and that surgeons will eagerly respond to this demand once they have a technology that allows them to confidently undertake the procedures.

The Future of Telesurgery

Telepresence clearly has the potential for bringing to outlying clinics the skills of expert specialists at regional medical centers. In a cost-conscious era, better use



7. Schematic representation of the Telepresence Surgery System configured for laparoscopic surgery. The surgeon will also control the laparoscope position.

of specialist skills and lower patient transport costs are both appealing. The rapid development of diagnostic telemedicine demonstrates that a real need is being met. Recent animal studies have demonstrated that microsurgical procedures, such as vascular repair, can be effectively performed by Telepresence [18]. Technologically, there seems to be no fundamental barrier to implementing telesurgery, although achieving fail-safe performance of both the sophisticated equipment and the communication link is a significant task, and propagation delays may present a challenge at distances greater than a few hundred kilometers. However, many important clinical considerations will bear heavily on the practicality of this telesurgery in the civilian sector.

As illustrated in Fig. 8, the appropriateness of Telepresence surgery for a particular patient at a particular clinic will depend upon the nature of the procedure to be performed and the clinic's in-house capabilities. If the procedure is minor and can be accomplished by someone on site (possibly with mentoring from a medical center), then telesurgery would not be indicated. If no one on site is competent to assist the surgeon, or if the clinic lacks the capability to deal with complications or postoperative care, then telesurgery would not be indicated. What lies in between is telesurgery's potential field of play. A high enough case load would justify the cost of the necessary capital equipment, training, and maintenance.

Comments and Conclusions

SRI has established that precise surgical procedures can be carried out with Telepresence. Within this decade, Telepresence surgery may become an established component of a new, technologically enhanced mode of cost-effective health care delivery.

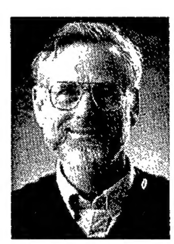
Because of the substantial medical and financial benefit that Telepresence will bring to laparoscopic and other minimally invasive procedures, its first routine use is expected to be *within* the individual hospital and surgical center. Telepresence surgical procedures have been demonstrated over distances of 160 meters, and we are working toward demonstrating animal surgeries over a much greater distance by using microwave and fiber-optic links. Mobile Telepresence surgical equipment may prove especially effective for trauma care in combat and in civilian disasters.

Because the stereographic images and the motions and forces can be readily scaled, microsurgeries of all kinds can be made easier with this technology. Arthroscopic procedures, especially difficult surgery on joints such as the wrist and shoulder, are good Telepresence candidates. In neurosurgery, excision of pituitary adenomas could benefit from the increased dexterity and tactile sensitivity of Telepresence. Eventually, neurosurgery under real-time magnetic resonance imaging could be performed by a Telepresence surgeon operating on a three-dimensional reconstruction that is immediately updated to show the actual tissue changes caused by the telemanipulated instruments (which, of course, would need to be nonmagnetic). One application of this combination of technologies might be the removal of colloid cysts from the brain. Gaining access to these cysts without disturbing surrounding tissues is now difficult. Computer-controlled exclusion zones could be established on the image prior to surgery to constrain the instrument's path.

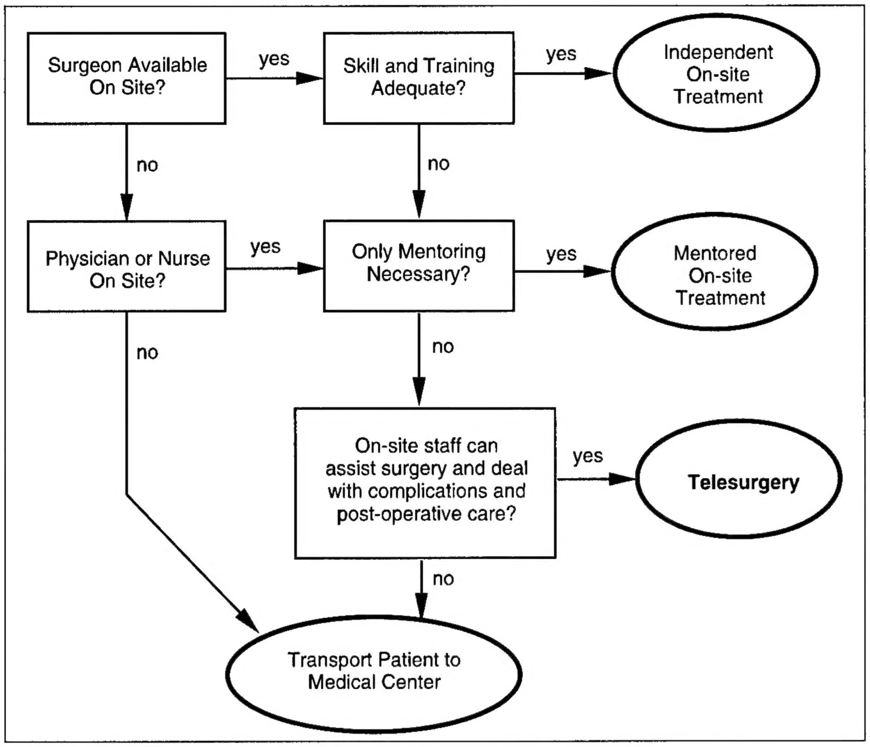
Acknowledgments

This work was supported in part by SRI International and in part by the National Institutes of Health, under Grant No. GM 44902, and by the Advanced Research Projects Agency (ARPA) under Contract N00014-94-C-0040, P.O. number 32858 from Assurance Technology Corp. (Government Contract N00014-93-D-2022), and Grant DAMD17-95-I-5019. The 577 vehicle was equipped as an operation theatre by Foster Miller, Inc., in cooperation with United Defense. The views represented in this article are those of the authors and do not reflect the official policy of the Department of Defense or the U.S. Government (approved for public release, distribution unlimited).

Philip S. Green received the B.S. and M.S. degrees in electrical engineering from the Johns Hopkins University and Stanford University, respectively. He joined SRI International in 1967 and formed its Ultrasonic Program shortly thereafter. From 1978 through 1992 he was Director of SRI's Bioengineering Research Laboratory where he was engaged in general laboratory management and business development, in the leadership and supervision of a broad spectrum of medical technology R&D projects, and in strategic consulting and technology licensing. Mr. Green is a Fellow of the American Institute of Ultrasound in Medicine and an SRI Fellow.

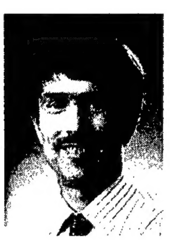


John W. Hill received the B.S. and M.S. degrees in electrical engineering from the University of Illinois in 1961, and 1963, respectively. He received the Ph.D. degree in electrical engineering from Stanford University in 1967. He has been at SRI International three times since 1967, with SRI's Bioengineering Group, Artificial Intelligence Center, and Robot-



8. Decision tree for utilization of remote telepresence surgery at local clinics.

ics and Machine Vision Group. In 1980 he left to found Microbot, Inc. and serve as the developer of the company's robotic product line. He is currently with SRI's Medical Technology Program. Dr. Hill's research interests include Telepresence, man-machine integration, and medical manipulators for surgery. Address for correspondence: SRI International, 333 Ravenswood Ave., Menlo Park, CA 94025. E-mail: john_hill@qm.sri.com



Joel F. Jensen received a B.S.M.E. from Ohio University in 1981 and an M.S.E.E. from Santa Clara University in 1991. He has led major product development projects in medical imaging and drug delivery and has served as a consultant to SRI clients in the area of medical products and markets. Mr. Jensen is an expert in the development of complex, miniature, servo-controlled electromechanical devices. He has been working in the telesurgery field for the last several years, in the areas of project planning, system development, and manipulator design. Prior to joining SRI in 1983, Mr. Jensen supervised a mechanical design group at Southwall Corporation, a manufacturer of optically coated films.

Ajit S. Shah received a B.S. degree in mechanical engineering from the University of California at Berkeley in 1981, and an M.S. degree in electrical engineering from Stanford University in 1982. In 1988, he received a joint Ph.D. degree in bioengineering from the School of Medicine at UCSF and from the College of Engineering at U.C. Berkeley. Dr. Shah has been with SRI since 1988 and is currently director of the Medical Technology Laboratory. Dr. Shah's research interests include medical instrumentation, medical imaging and clinical testing. Prior to joining SRI, Dr. Shah was the founder of Ajida Technologies, a company dedicated to the development of PC-based instrumentation. He is an active member of the Society of Magnetic Resonance in Medicine.

References

1. **Thring M:** *Robots and Telechirs*, Ellis Horwood Ltd., 1983.

2. **Charles S, Williams R, Hamel W:** Design of a surgeon-machine interface for teleoperated microsurgery, *Proc. IEEE Engng in Medicine and Biology*, 11th Annual Int Conf, 883-884, 1989.

3. **Guerrouad A, Vidal P:** SMOS: Stereo-telemanipulator for ocular surgery, *Proc. IEEE Engng in Medicine and Biology*, 11th Annual Int Conf, 879-880, 1989.

4. **Gayed M, et al:** An advanced control manipulator for surgical applications, *Systems Sci*, Vol. 13, 123, 1987.

5. **Satava R:** Surgery 2001: a technology framework for the future, *Soc Am Gastrointestinal Surgeons* (SAGES), Washington, DC, 1992.

6. **Green P, Satava R, Hill J, and Simon I:** Telepresence: advanced teleoperator technology for enhanced minimally invasive surgery, *Soc Am Gastrointestinal Surgeons*, Washington, DC, April 1992. This paper was also presented at *Medicine Meets Virtual Reality*, San Diego, CA, 1992.

7. **Satava R:** Telepresence: endoscopy in the year 2000, *Am Assoc Gynecological Laparoscopists*, IL, 1992.

8. **Simon I:** Virtual reality, robotics, and surgery in the 21st Century, *Soc Urology and Engng at the Am Urological Association*, San Antonio, TX, 1993.

9. **Preising B, Hsia T, and Mittelstadt B:** A literature review: robots in medicine, *Proc. IEEE Engng in Medicine and Biology*, 0739-5175/91/0600-13, 12-22, 1991.

10. **Taylor R, et al:** An image-directed robotic system for precise orthopaedic surgery, *IEEE Trans on Robotics and Automation*, 10 (3), 261-275, 1994.

11. **Ng W, Davies B, Hibberd R, and Timoney A:** Robotic surgery: a first-hand experience in transurethral resection of the prostate, *Proc IEEE Engng in Medicine and Biology*, 120-125, 1993.

12. **Taubes G:** Surgery in cyberspace, *Discover*, 84-94, Dec 1994.

13. **Neisius B, Dautzenberg P, Trapp R, and Buess G:** Robotic manipulator for endoscopic handling of surgical effectors and cameras, *Proc 1st Int Symp on Med Robotics & Computer-Assisted Surgery*, Pittsburgh, PA, 169-175, Sept 22-24 1994.

14. **Bellamy R, and Zajtchuk R, eds:** *Textbook of Military Medicine*, Off Surg Gen, USA, 1991.

15. **Hill J, Jensen J, Green P, and Shah A:** Two-handed telepresence surgery demonstration system, *6th Topical Meeting on Robotics and Remote Systems*, Monterey, CA, Feb 5-10, 1995.

16. **Bowen TE, and Bellamy RF:** *Emergency War Surgery*, U.S. Gov't Printing Off, 1988.

17. **Hill J, Green P, Jensen J, and Shah A:** Telepresence surgery demonstration system, *Proc IEEE Conf Robotics and Automation*, San Diego, CA, 3, 2302-2307, 1994.

18. **Bowersox J, Shah, A, Jensen J, Hill J, and Green P:** Applications of a telepresence surgery system in vascular surgery, to be presented at the Spring 1995 meeting, *Soc Vascular Surgery*.